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THE SIGNIFICANCE OF THE FRAMEWORK OF THE CONTINENTS

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ABSTRACT

Existing mountain ranges, following the borders of the present continents so closely in many parts of the globe as to indicate a genetic relationship to these borders, lead to the belief that the folded ranges of earlier ages also arose along the borders of the continents.

A comparison of trend lines of the successive generations of folding from pre-Cambrian to the present shows, in many cases, that the later foldings have developed either on the sites of the earlier foldings, or in belts adjoining and more or less parallel to the earlier mountain chains. The repetition of similar stress conditions has produced a repetition of the results. Also by the transfer of material as sediment, mountains of a younger generation receive a direct inheritance from mountains of an older generation, which inheritance has exerted an influence on the general trend lines.

The old trend lines afford one of the best means of delineating ancient continents and ocean basins. The main lines of the continental platforms seem not to have changed very radically, as a rule, throughout known geologic time. Postulated continents, like Gondwanaland, Atlantis, etc., where ocean basins are today, cannot be recognized under this system.

INTRODUCTION

A recent controversy over the trend lines of pre-Cambrian folding is the excuse for reviewing briefly some of the groundwork of both historical and structural geology, and for emphasizing the interrelationship and bearing of some of the fundamental facts which have been more or less familiar to geologists for a long time. While a few teachers of geology have been hammering these principles in the classroom for years, among the geological profession as

a whole there is the widest possible divergence of opinion and belief. The theories of Wegener, Ampferer, etc., and the belief in Gondwanaland and other continental masses over the sites of the present ocean basins, show how widely apart the interpretation of geologic records can lead investigators.

Ruedemann has recently published an admirable synthetic study of the pre-Cambrian trend lines of the world and of their origin.[1] As the result of a very painstaking review of the available data, he has reached the general conclusion that the pre-Cambrian areas exhibit a more or less orderly structural plan. Although many subordinate departures tend to complicate the patterns, nevertheless, when viewed in the large, each of the early continental masses is characterized by an individual structural plan. This being so, the pre-Cambrian lands may be blocked out, grouped into continental masses, and mapped on the basis of the trends of pre-Cambrian folding and foliation. Ruedemann's chart (Fig. 1) represents three large continental masses: I, Archi-America, comprising North America, Greenland, and enough of the North Atlantic so as just to include Western Ireland and the northwestern extremity of Scotland; II, Archi-Eurasia, comprising all of Europe and Asia which lies north of a line drawn from the Danish peninsula to the Gulf of Tonkin; and III, Archi-Gondwana, a vast continent extending from Eastern Brazil across the Atlantic and Indian oceans so as to include nearly all of Africa, Arabia, India, and most of Australia. These continents, as postulated, differ greatly from the present continents in location and outline, and show little relation to them. But it is stated in conclusion that "shrinkage appears to have been the sole cause of the folding, and the existence and configuration of the continental and oceanic segments the controlling agency in the direction of the trend lines of the folds."[2] It is also stated as a general proposition that "apparently a great portion of the Paleozoic folds do not diverge greatly in their directions from the preceding pre-Cambrian trend lines and thus have remained, to a large extent,

[1] Rudolph Ruedemann, "The Existence and Configuration of Pre-Cambrian Continents," *New York State Mus. Bulletins 239–40, Seventeenth Rept. of the Director, 1920–21*, pp. 67–152.

[2] *Op. cit.*, p. 146.

under the influence of the original trend lines inherited from pre-Cambrian time."[1]

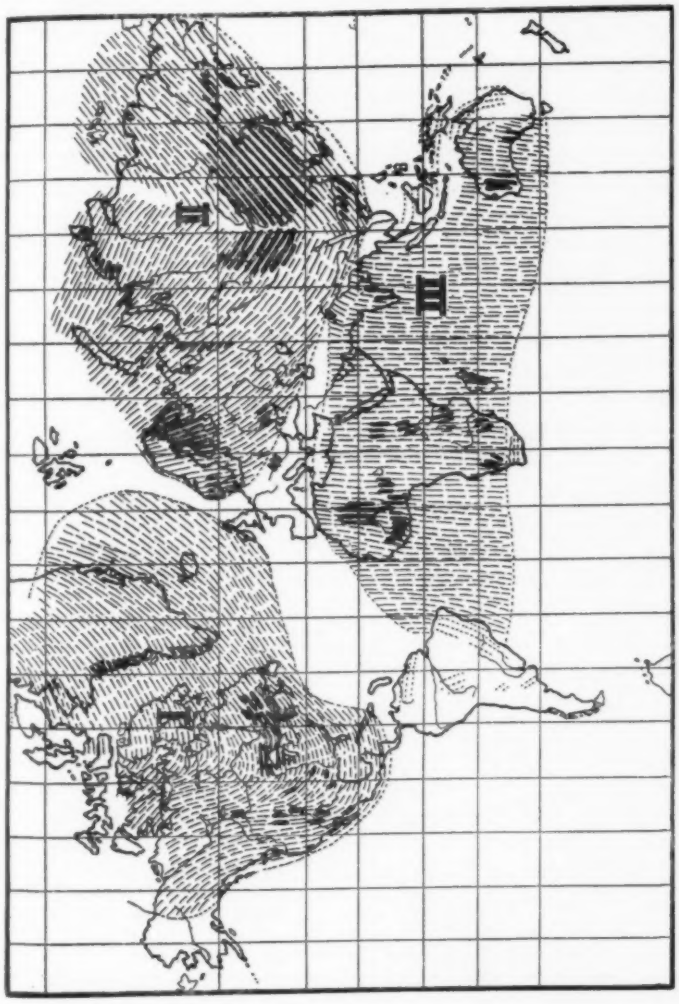

FIG. 1.—Chart of the trend lines of folding and foliation of pre-Cambrian age, indicating the pre-Cambrian continental areas. I, Archi-America; II, Archi-Eurasia; III, Archi-Gondwana; ▮▮▮, observed direction of trend lines; ▯▯▯, inferred directions; ▯▯▯, fold directions of post-Proterozoic age in pre-Cambrian rocks, in part probably of posthumous character. (From Ruedemann.)

[1] *Ibid.*, p. 115.

Ruedemann's generalizations have since been challenged by W. J. Miller, whose studies of the pre-Cambrian literature of North America have seemed to him to point toward much greater irregularity of trend lines.[1] While Ruedemann contended that Archeozoic folding was nearly universal, Miller claims that the older pre-Cambrian rocks of North America have not been everywhere intensely folded, but that inasmuch as a localization of orogenic forces, both in space and in time, has characterized the long post-Cambrian history of the continent, it is more reasonable to believe that similar localization obtained during pre-Cambrian time. He does not believe that North America reacted as a "unit against the diastrophic forces active in pre-Cambrian time," as advocated by Ruedemann.

Ruedemann has replied that an undue emphasis of cross-folds and structures of purely local significance tends only to hide and confuse the general picture of the fold system and thus to cause one to miss its meaning.[2] The chief purpose of the later paper, however, is to show to what extent the pre-Cambrian grain has controlled the later geologic history of North America. It is pointed out that in general the inundations of the Paleozoic seas, the present strikes of Paleozoic and later rocks, as well as the main lines of the present physiographic features, display an arrangement related to the pattern of pre-Cambrian trend lines, and the conclusion is put forth that these several features have in the main been controlled by the original grain of the continent.

MEGADIASTROPHISM

This is not the place to argue the merits of the various theories of earth deformation. Instead, we will consider a solid earth composed of elastic, rigid material, as demonstrated by the behavior of seismic tremors, the nutation period of the earth, and the tidal researches of Michelson, Gale, and Moulton,[3] and built up by the

[1] William J. Miller, "Pre-Cambrian Folding in North America," *Bull. Geol. Soc. Amer.*, Vol. XXXIV (1923), pp. 679–702.

[2] Rudolph Ruedemann, "Fundamental Lines of North American Geologic Structure," *Amer. Jour. Sci.*, Vol. VI (1923), pp. 1–10.

[3] A. A. Michelson and H. G. Gale, "The Rigidity of the Earth," *Jour. of Geol.*, Vol. XXVII (1919), pp. 585–601. F. R. Moulton, "Theory of Tides in Pipes on a Rigid Earth," *Astrophys. Jour.* (1919), pp. 346–55.

accretion of heterogeneous material in accordance with the planetesimal hypothesis.[1] From an early state of growth several selective processes operated in favor of higher specific gravity beneath the ocean basins than in the outer part of the land masses.[2] The differences in specific gravity in the outer portion of the earth have become considerable. From a study of the chemical composition of the rocks, H. S. Washington gives the average densities of the continents and ocean floors as follows:[3]

TABLE I

Segment	Height in Meters	Density (Water-Free Basis)
North America	700	2.782
South America	580	2.783
Europe	300	2.790
Africa	650	2.780
Asia	950	2.769
Australia	350	2.814
Atlantic Ocean	−4,116	2.888
Pacific Ocean	−4,520	3.087

These estimates check with the geodetic determinations that the oceanic segments, in their outer portions at least, are of higher specific gravity than the continental segments, as is, of course, well known.

In the rearrangement of the planetesimal material in its passage from the original condition of heterogeneous aggregation to the present earth by the operation of heat and great pressure, a large amount of condensation and shrinkage is involved. On the assumption that the earth originally had the density of average meteoritic material, 3.69, and that this has been increased to 5.53, the present density of the earth, a circumferential shortening of 3,594 miles, or a radial shortening of 572 miles, is involved.[4] If, however, the high specific gravity of the deep interior is partly due to a concentration

[1] T. C. Chamberlin, *The Origin of the Earth* (1916), chap. vii, pp. 130–58.

[2] *Ibid.*

[3] H. S. Washington, "Isostasy and Rock Density," *Bull. Geol. Soc. Amer.*, Vol. XXXIII (1922), p. 404.

[4] T. C. Chamberlin, "The Order of Magnitude of the Shrinkage of the Earth Deduced from Mars, Venus, and the Moon." *Jour. of Geol.*, Vol. XXVIII (1920), pp. 1–17.

there of heavier elements like metallic iron according to a hypothesis long entertained, the amount of shrinkage would be notably reduced from this figure, though still remaining large.[1] Any except rough, tentative estimates on this basis seem inadvisable, owing to the uncertainties involved. However, assuming that compression has caused the increase in density allowed for the outer 1,600 kilometers by Williamson and Adams' density-depth curves (p. 419), a circumferential shortening of the earth in the neighborhood of 600 miles would be indicated. If, in addition, the remaining inner portion of the earth was compressed only as much as this, the total shortening would be in the neighborhood of 1,000 miles. But it would seem rather to be expected, in accord with the newer theories of the structure of matter, that new types of organization in favor of greater density would arise in accommodation to the tremendous pressure within the deep interior and that this conditional estimate of 1,000 miles of shortening is too low.

The time-honored theory of earth contraction due to cooling has failed to meet the requirements of the case in at least two important ways: (1) the amount of crustal shortening observed is greater than can have arisen from the cooling down of a molten globe even under the most favorable assumptions;[2] and (2) during Tertiary time alone the east-west Eurasian and the north-south American orogenies, besides minor crumplings, testify to scores of miles of crustal shortening within that period of time, and yet we cannot say with certainty that there has been any cooling of the interior of the earth during the Tertiary. The development of heat may have gone on as

[1] E. D. Williamson and L. H. Adams, "Density Distribution in the Earth," *Jour. Wash. Acad. Sci.*, Vol. XIII (1923), pp. 419–20.

[2] A recent attempt by Harold Jeffreys to demonstrate the adequacy of cooling to produce the crustal shortening required by the folded and faulted mountain ranges of the globe has taken into account principally the more familiar Tertiary foldings plus a few sporadic ranges of Paleozoic and Mesozoic age. Some of the Tertiary crustal shortening, much of the Mesozoic and Paleozoic, and all of the vastly greater pre-Cambrian folding and shortening have been very curiously and carelessly left out of consideration. The continent of Australia has been ignored completely. Adding to the shortening which Jeffreys has put into the mathematical mill, only a minor fraction of that which he has left out of consideration, turns the supposed demonstration decisively in the opposite direction. (Harold Jeffreys, *The Earth. Its Origin, History and Physical Constitution* [Cambridge, 1924], p. 136.)

rapidly as it was lost. It may even have gone on more rapidly. Certainly there has not been enough cooling in the few million years involved to account for such shortening. But, on the other hand, the planetesimal conception, recognizing and requiring strong condensation by rearrangement under compression in the interior, involves inevitably the mechanism for large-scale earth shrinkage. The large crustal shortening demonstrated by the field data is thus natural and is given an adequate theoretical basis, which it did not have before.

As the rearrangement in favor of greater density must go on throughout the globe, beneath both continents and ocean basins, the shrinkage should be general, and the resulting circumferential compressive stresses must develop throughout the entire peripheral portion of the spheroid, though probably not reaching the same intensity everywhere. Strong tangential thrusting stresses would develop beneath both the continental and the oceanic areas. These are the ultimate forces concerned in megadiastrophism.

In the shrinkage process the oceanic regions, being composed of denser material, naturally take the lead in sinking, as has been clearly stated in the textbooks. Though the sinking be general, the smaller and lighter continental areas would be pushed upward relatively by the lateral crowding. These have been treated as segments,[1] the suboceanic masses being the master-segments and the continents, as squeezed segments between oceanic segments, perhaps working on the wedge principle[2] The general relations may be expressed in a diagram (Fig. 2).

The differentiation into continental protuberances and oceanic depressions, according to the planetesimal hypothesis, began early in the formative stages.[3] The protuberances and the basins should have been well differentiated by the time of formation of the oldest Archean rocks which we reach today. Therefore in Archeozoic times, as in subsequent times, when the growing internal strains reached the yielding-point, it would be the oceanic segments which

[1] T. C. Chamberlin and R. D. Salisbury, *Jour. of Geol.*, Vol. I (1904), pp. 520–24.

[2] R. T. Chamberlin, "The Intimations of Shell Deformation," *Jour. of Geol.*, Vol. XXIX (1921), pp. 416–25.

[3] *The Origin of the Earth*, chap. viii, pp. 159–225.

would have precedence in sinking in consequence of (1) their denser material and (2) the upsetting of isostatic equilibrium by denudation of the land areas and aggradation of the sea bottom.

In taking the lead in sinking into a smaller circumference and in settling most, the oceanic segments, in their outer portions, will crowd the borders of the adjacent continental segments. At the same time the lighter rocks of the continental segments are probably on the average weaker than the denser rocks of the ocean segments, and the upcurving sides of the continental platforms offer less resistance to lateral thrusting than the downcurving margins of the ocean basins. But this crowding of the continental shelves by

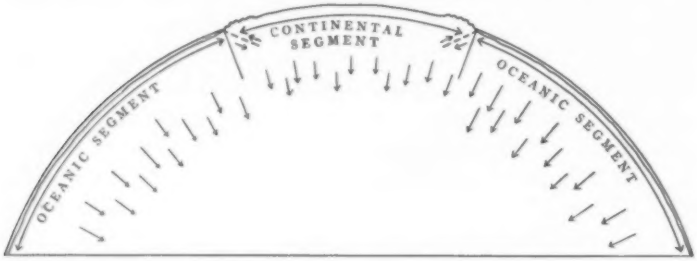

FIG. 2.—Diagram to illustrate deformation of a continent. Arrows pointing toward center of earth indicate general condensation. Long arrows represent tangential compressive stress. All segments sink, but the continent is wedged up somewhat relative to the oceanic segments. Dash lines represent shear under the continent. Vertical lines represent relations of segments before diastrophism.

the oceanic segments simply in consequence of the greater sinking of the latter, however, is not taken as the chief source of the lateral thrusting which deforms the continents. Far greater horizontal compressive stresses arise from the sinking of all segments in consequence of the rearrangements and condensation going on throughout the globe. This is a matter which has often been overlooked or misunderstood. Each continental mass is under strong compressive stress derived in part within itself. In each case it is rather the final overbalancing or trigger effect, which comes from the greater sinking of the adjacent oceanic segment. But while by no means the main source of compressive stress, the final overbalancing is of great importance in determining and directing to a considerable

extent the location and alignment of the belts of greatest yielding and strongest deformation.

If the final overbalancing or trigger effect comes from the activity of an ocean segment in crowding against one or more adjacent continental segments, the effect, other things being equal, will be most strongly felt in the marginal portions of the affected continental mass or masses. Unless other important factors enter strongly enough to control the operation, the belts of greatest deformation will naturally be located near the borders of the continents and more or less parallel to or concentric with these borders. One should expect to find the majority of the more important mountain systems of the globe (though not necessarily all of them) along the margins of the continents and, in the main, parallel to these margins.

If we turn to the maps we see how generally, the world over, the present and ancient mountain chains have paralleled the borders of the present continents. This is not a new observation, for it has been stated many times before by various writers, but the wide prevalence of this relationship, and particularly its seeming fundamental importance, have been so generally overlooked or lightly brushed aside in favor of a great variety of other interpretations, based, it seems to the writer, on slight evidence, real or fancied, that it ought to be brought sharply to the front and emphasized.

TREND LINES OF THE CONTINENTS

North America.—From Alaska to Panama, the western Cordillera parallel approximately the present Pacific Coast line. Wherever the coast line makes a major turn the structural lines turn likewise. The most pronounced curve of the coast is in southeastern Alaska. Just as the coast turns sharply westward near Mount St. Elias, just so the chains nearest the Pacific, the Coast ranges, the St. Elias Range, Chugach, Alaskan ranges, etc., make a grand swing parallel to the westerly curving of the Pacific shores. Some of these structures are of Tertiary age, others Jurassic, while the Chugach folding apparently goes back to the Paleozoic. Yet they all follow the curving trend of the Pacific border. The Rocky Mountain system, farthest from the Pacific, does likewise. Before

reaching the Arctic Ocean, the northern Rockies bend westward into Alaska. On the northern margin of the continent the Endicott Mountains parallel the adjacent Arctic Ocean from Canada to Bering Strait, with a probable continuation along the Arctic shores of northeastern Siberia. Brooks believes that this system of folding is traceable for at least 1,500 miles parallel to the Arctic Ocean.[1]

On the Atlantic side of North America, the Taconic (post-Ordovician), Brunswickian or Shickshockian (post-Hamilton), and Appalachian (post-Permian) foldings parallel closely the present Atlantic Coast. It is a particularly striking fact that the southern Appalachians in Alabama swerve westward, ignoring the peninsula of Florida (probably a post-Permian addition to the continent), and follow in alignment the Gulf Coast. A continuation of late Paleozoic folding through the Ouachita, Arbuckle, and Wichita Mountains still further parallels the Gulf border. Branner long ago called attention to this westerly extension of the Appalachian folding.[2] A fainter line of Appalachian folding and fracture farther inland runs from north-central Pennsylvania across West Virginia, central Kentucky, and southern Illinois, to the Ozark Mountains.[3] While the main Appalachian folds disappear under younger sediments in central Alabama and lie deeply buried beneath the Mississippi deltal deposits, this feebler, more inland expression of that folding is useful in revealing the general trend of the concealed portion of the main chain. The Appalachians curve in harmony with the Atlantic and Gulf coasts.

The ancient pre-Cambrian folded ranges and batholithic intrusions, as brought out by Ruedemann, trended northeast-southwest in Quebec and eastern Ontario, becoming essentially east and west in the vicinity of Lake Superior.[4] These curving structures show resemblance to the later Appalachian-Ouachita lines of disturbance, the chief difference being that they are closer to the heart of the

[1] Alfred H. Brooks, *Bull. Geol. Soc. Amer.*, Vol. XXXV (1924), p. 98.

[2] John C. Branner, "The Former Extension of the Appalachians across Mississippi, Louisiana and Texas," *Amer. Jour. Sci.*, 4th ser., Vol. IV (1897), pp. 357–71.

[3] James H. Gardner, "Extension of the Chestnut Ridge Disturbance from Central Pennsylvania to the Ozark Mountains of Missouri," *Bull. Geol. Soc. Amer.*, Vol. XXVI (1915), pp. 477–83.

[4] Rudolph Ruedemann, *New York State Mus., Seventeenth Rept. of Director, 1920–21*, pp. 83–93.

continent and farther from its curving borders. Further information is needed from the Cordilleran tract before basing too much upon the trend of its pre-Cambrian structures. In the northeast, the remarkable parallelism between the pre-Cambrian trends and the present coast of Labrador has been brought out by Daly.[1]

In Mexico, the Sierra Madre Oriental face the Atlantic, as the Sierra Madre Occidental face the Pacific.

South America.—Nothing can be more evident or striking than the minuteness with which the Andean chains follow the Pacific Coast from one end of the continent to the other. Genetically they must be related. In northern Colombia, where the continent comes to an end, the western chain of Andes plays out in part and in part swings into the Isthmus of Panama, while the eastern chain of Andes bends to the east and follows the Venezuelan Caribbean coast as far as Trinidad. The trend lines in the Guianas appear to be related to the Atlantic. On the eastern side of South America, throughout the length of Brazil, the ancient trends, still visible in the mountains of today, are scarcely less striking in their relation to the present shores. Where the present Brazilian coast makes a nearly right-angle bend at Cabo Frio, east of Rio de Janeiro, the long Serra do Espinhaço, or backbone range of Brazil, makes an almost identical bend, and yet its structures, which swerve like the present coast, were formed in pre-Devonian times. The Serra do Mar, Serra da Mantequeira, and other ranges also make corresponding bends. In Argentina, however, some of the Paleozoic trend lines run northwest and southeast, pointing, as they are prolonged northwestward, toward the Bolivian and Peruvian Andes. This orientation can hardly be urged against the general proposition which we are considering because if, in projecting these structures southeastward under the shallow seas, they be curved slightly to the south they would follow the borders of the present broad continental shelf toward the Falkland Islands which exhibit strong Paleozoic folding.

A glance at the relief map of South America shows how largely the continent is blocked out by a peripheral framework of mountain chains. This framework is broken only where the big rivers, the

[1] R. A. Daly, chapter in *Labrador: The Country and the People*, by W. T. Grenfell and Others (1909), pp. 88–89.

Orinoco, the Amazon, and the Paraná, have cut through the old chains and in their valley bottoms have buried much of the ancient structure beneath younger sediments. The broad interior basins of these river systems constitute the great heart of the continent.

Africa.—An inspection of the physical map of Africa shows that south of the Equator the principal existing mountain ranges tend to be near the coasts of both the Atlantic and Indian oceans and concentric with them. The arcuate mountainous belt around the blunt southern end of Africa is particularly noticeable. In Cape Colony there have been two periods of strong folding, one before the deposition of the Devonian Cape system, and the other after deposition of the Permo-Carboniferous Ecca series. "The general parallelism between the two systems of folds points to a repetition of the folding along the same lines at a great interval of time."[1] North of Cape Colony and in fact throughout much of the remainder of Africa, the old crystalline rocks display predominant north-south trending structures as emphasized by Ruedemann. These seemingly are less closely related to the present shore lines, but are nevertheless in harmony with a squeezing of the African block between the Atlantic and Indian Ocean segments. These deformations were early in geologic history, Africa having been a comparatively stable mass during later geologic history. This prevailing north-south grain occurs both near the coasts and far in the interior.

The land mass of Arabia, cut off today by the downwarped and downfaulted Red Sea trough, would seem to belong to the African continental mass. Continuing the east coast line from Cape Guardafui to the Sea of Oman, the Persian Gulf and the valley of the Euphrates would delimit the continent on the northeast, and these together with the Mediterranean would separate the African land mass from the Eurasian land mass. This low-lying belt of division is a part of the submerged belt which in earlier geologic times, as the Tethys Strait, separated the continental units. Thus delimited Arabia fills out the northeast corner of the African block. Like Egypt, it has suffered little from folding in later geologic times. On the northwestern side of Africa the Tertiary Atlas chains follow closely the Mediterranean and Atlantic shores.

[1] A. W. Rogers and A. L. Du Toit, *An Introduction to the Geology of Cape Colony* (2d ed., 1909), pp. 26–27.

Australia.—The whole eastern coast of Australia is paralleled by north-south ranges which were folded principally in Paleozoic time. The Mount Lofty Range in South Australia has a similar north-south trend. In Central Australia, on the other hand, the general structural trends seem to be largely east and west. Being in the heart of the continent, they are not so obviously related to the coasts, but as the long dimension of Australia is east and west, one would naturally expect east and west trend lines to prevail in whatever structures there were in Central Australia. In Western Australia the axes of folding of the pre-Cambrian rocks, which are the dominant structural lines of the region, run in general northwest and southeast, approximately with the shores of the Indian Ocean north of Cape Leeuwin.

Australia, however, appears to be the least strongly developed of the continental masses. Many islands and archipelagoes cluster about it, giving the whole the appearance of an abortive continent. So its extent and outlines during the various geologic ages have been the occasion of much difference of opinion,[1] and the framework case for Australia may seem, in consequence, less satisfactory to some.

Europe.—Europe and Asia are the most irregular and unsymmetrical of the continents. Their mountain chains are likewise the most diverse. But even here some alignment is at once apparent. The great Caledonian system, formed at the close of the Silurian, parallels the edge of the present continental shelf, though not the present irregular shores, in striking fashion. The eastern half of the Caledonian wedge is the dominating structure of the Scandinavian peninsula. From the North Cape its structures follow the Norwegian coast throughout nearly the whole of its extent, and then, continuing across the shallow epicontinental North Sea, the western half of the Caledonian structural wedge is responsible for most of the grain of Scotland and Ireland. In the vicinity of Ireland, however, the folded belt would seem to veer sharply to the south, for the configuration of the ocean bed west of Ireland lends no support to the hypothesis that the great chain continued southwest out into the Atlantic Ocean Basin, while, on the other hand,

[1] W. N. Benson, "Paleozoic and Mesozoic Seas in Australasia," *Trans. New Zealand Inst.*, Vol. LIV (1923), pp. 1–62.

evidences of Caledonian folding are found in Brittany,[1] in the Central Plateau of France,[2] as north-south trending folds in the Pyrenees,[3] in the central Meseta of Spain, and onward in the Oran region of the Sahara Desert.[4] Thus the Caledonian chains which, north of Ireland, follow the borders of the continental platform, seem to bend south along with the western margin of the European continent and to continue on into northwestern Africa. Thus delineated, their relation to the margin of the Atlantic Ocean Basin could hardly be closer.

The Carboniferous Hercynian and Tertiary Alpine chains, however, present much greater irregularity. The Hercynian system of mountain folding has even been projected by many geologists, following the lead of Marcel Bertrand, from the coast of Britain and France across the Atlantic Ocean to the shores of North America and thence into the Appalachian Mountains.[5] But against this bold conception is the fact that the Hercynian and Appalachian folding occurred at quite different times. Furthermore, a mountain range once deeply submerged beneath an ocean, where erosion is negligible, should remain practically unchanged for long periods of time. Aggradation in the middle of an ocean should bury it but slowly. The great ranges should be there today, greater than on land, where they have been reduced, but unless the Atlantic charts are very defective, they do not appear there. It would be necessary to conceive of the Hercynian system extending across the Atlantic as a land mass and then reduced to low relief before submergence. Such an assumption is a violent one. At the west end of Brittany, where such a postulated range should take its jump across the Atlantic, it is to be noted that the trends of the folds are converging rapidly, perhaps not to go much farther. The old chain runs west along the northern coast of Spain, but near Coruna and Cape Finisterre it turns sharply southward in more than a 90° turn and con-

[1] L. de Launay, *Géologie de la France* (1921), pp. 37, 85, Fig. 6.

[2] *Ibid.*, p. 147.

[3] Joseph Roussel, *Études Stratigraphic des Pyrénées*, Paris, 1893.

[4] R. Chaudeau and E. F. Gautier, "Sur le Structure géologique du Sahara central," *Comptes rendus*, Vol. CLXI (1905), pp. 374–76.

[5] Marcel Bertrand, "La Chaîne des Alpes, et la Formation du Continent Européen," *Bull. Soc. Géol. de France*, 3d ser., Vol. XV (1886–87), pp. 423–47, map on p. 442.

tinues backward southeast into the Iberian peninsula. The Tertiary Pyrenees, apparently pointed for the Atlantic, swerve and are continued in the Cantabrian Mountains, but they likewise do not extend beyond the borders of the continental shelf. In this study we will not consider doubtful prolongations of mountain systems out into the oceans, but confine ourselves to the observed chains.

The details of the sinuous lines of the Hercynian and Alpine chains may appear to defy orderly arrangement, but in the large these major zones of deformation extend in an east-west belt across the central and southern portion of the Eurasian land mass, though the two great systems of folding did not affect identically the same areas. In spite of their sweeping curves, irregularity in detail and distance from the continental border in places, they are nevertheless essentially a great marginal belt, or belts, which constitute the southern framework of the vast Eurasian mass.

Unlike the other continents, of simpler and fairly regular pattern, Eurasia is a more composite mass and a bordering framework is less apparent. Nevertheless, with the Caledonian system constituting a northern and western bordering frame, and the Hercynian-Alpine system a southern bordering frame, the larger portion of Europe remains between, comparatively undeformed. The inclosed portion comprises the plains of Germany, Poland, and practically all of Russia. It is not so perfect a frame, but still it is a frame.

Asia.—Asia continues eastward the general characteristics of the Eurasian continental mass. If we consider Arabia a corner of the African block, the chains of Southeastern Europe continue through Asia Minor and through Persia and Baluchistan to India as peripheral ranges. Thus, though strongly arcuate in detail, the great mountain system follows the southern border of the Eurasian continent from the Pyrenees to the western frontier of India. East of the Hindu Kush knot, however, the Himalaya, Kuen Lun, Tian Shan, Altai, and other ranges occupy more nearly the heart of Asia. They continue onward in essentially east and west alignment until they approach the Pacific, where some chains die out, while others curve into general parallelism with the Pacific border.

Directly east of the great Tibetan Plateau, the post-Paleozoic folded ranges of Szechuan, Western China, though variously shown on maps, are observed in the field to trend northeast-southwest,

approximately parallel to the China coast. Similar trends seem to prevail throughout the mountains of the whole of eastern China. In northern China, eastern Mongolia and Manchuria, the parallelism continues in the Wu Tai Shan,[1] Khingan, Sikhota-Alin, and other chains so graphically shown on Kropatkin's orographic map of Asia.[2] The ranges continue onward toward Bering Strait. The influence of the Pacific segment seems to have strongly affected the whole eastern Asiatic border. In general, also, the festoons of islands, from Kamchatka to the East Indies, lie off the eastern shores in essential parallelism. The belt of northeast-southwest trending folds is thus one of great width—from Lake Baikal to Japan, approximately 2,000 miles.

Outlying festoons, like the Aleutian Islands, Marianne and Ladrone Islands, and others, each with an inner line of upwarp and volcanic extrusion and an outer zone of downwarp (the present deeps), indicate that the belts of folding are not confined to the continents but do occur also within the oceanic segments though more or less related to the segment borders. In these cases the charts indicate unmistakably the submarine upswellings and downwarps; they are not left to conjecture.

Three anomalies stand out prominently—the peninsula of India between the Himalayas and the Indian Ocean, the southward continuation of some of the ranges from eastern Tibet through Burma and Siam into the Malay peninsula, and the north-south chain of Ural Mountains in the heart of the land mass. India seems to have been strong and stable, so that the folding occurred in the weaker belt of thick sedimentation to the north of the peninsula. From Burma two concentric arcs of folding extend south and then southeast, the outer chain linking together the Andaman Islands, Nicobar Islands, Sumatra, Java, and the Lesser Sunda Islands, while the inner chain extends through the Malay peninsula. This strongly disturbed belt lies between two great oceanic segments, where squeezing might be expected to manifest itself in concentrated form.

[1] Bailey Willis, *Research in China*, Vol. II, Carnegie Institution of Washington (1907), Plates VII and VIII.

[2] Peter Kropatkin, "The Orography of Asia," *Geog. Jour.*, Vol. XXIII (1904), pp. 176–207; 331–61.

The Ural Mountains are frequently cited as a folded belt not related to the border of a continent nor parallel to its shores. As such, they seem an anomaly. Nevertheless, if folding is to be pictured as the work of stresses developed within the continental segments themselves as well as from lateral crowding by the oceanic segments, there is no inherent reason why yielding should not take place in the heart of a continent, if a sufficiently weak zone exists there. The Eurasian land mass is so vast that some means of relieving east-west stresses, as well as north-south stresses, might well be expected in the interior of the large and perhaps unwieldy block. Such accommodation would be afforded by the Urals.

GENERAL RELATIONSHIPS

Restrictions of space have necessarily limited the foregoing discussion of the world's tectonic lines to the barest outlines. While a far more complete analysis is really required, even this skeleton outline indicates the basis for several generalizations which are more or less familiar to students of dynamic geology. These are:

1. In each of the different continents the larger structural lines, as revealed by folds, foliation, thrust faults and intrusions, exhibit a noticeable parallelism with the borders of the continent. In each, orogenic diastrophism has been most prevalent near the continental margins, though it has in many places occurred farther inland as well.

2. This marked tendency of the folded ranges to form parallel to the margins of the continents does not seem to have been confined to any particular episode in the earth's history, but on the contrary has characterized, in varying degree, the whole span of known geologic time from the Archean to the present.

3. Later deformations are inclined to show strong relationship to the earlier lines of disturbance, either by occurring within the same folded and fractured belts, or by developing alongside of the older belts more or less in alignment with them.

It is true that some of the earlier tectonic lines show less intimate relationship to the borders of the present continental platforms than do the more recent ones. But here allowance is to be made for reasonable changes in the outline of the continental platforms

during growth and development. In postulating changes in the continental platforms however, the writer believes in limiting the changes strictly to minor details in evolutionary development, and not to countenance the more radical, reckless moving about of the earth's major relief features like pieces on a chessboard. Even relatively minor changes allowed in continental evolution will be found to reduce the number of apparent exceptions to the rule of parallel arrangement.

Pre-Cambrian folding has affected wider areas than subsequent deformations, though considerable areas of pre-Cambrian rocks are known to have escaped the more intense phases of diastrophism. But in determining the extent of pre-Cambrian deformation we are handicapped by the fact that it is chiefly in those areas which have, at some time, suffered notable deformation and uplift that the pre-Cambrian rocks are visible today, while over more than half of the land surface of the globe, particularly the areas of flat-lying sedimentaries which have escaped Paleozoic and later deformation, and so perhaps much of the earlier deformation as well, we know nothing of the structure of the pre-Cambrian. In such areas the pre-Cambrian may also show less deformation. Later studies extend the doctrine of uniformitarianism to the earliest-known times instead of commencing with the beginning of the Cambrian. If this is well founded, as it seems to be, we may expect to find that pre-Cambrian processes differed from post-Cambrian more in degree than in kind. The observed trend lines reveal in general common relationships throughout the different ages.

Godwin-Austen,[1] Richthofen,[2] and others recognized at an early date that new folds in an already folded region tend to follow the old trends. Suess has made much of this principle of persistent or inherited folding, which, under the name, "posthumous folding," plays such an important rôle in his interpretation of the face of the earth.[3] Ruedemann, following Suess, has brought out clearly the relationship between pre-Cambrian folding and the "posthumous

[1] R. Godwin Austen, *On the Possible Extension of the Coal-Measures beneath the Southeastern Part of England* (1856), p. 62.

[2] Ferdinand von Richthofen, *China*, Vol. II (1882), p. 637.

[3] Edward Suess, *The Face of the Earth*.

Paleozoic folds" whose location has been greatly influenced, if not determined in large measure, he believes, by the former.[1] Much detailed evidence has been adduced to indicate that the Paleozoic fold directions were inherited to a large extent from pre-Cambrian time. Whatever explanation is offered for this accordance of trends, the establishment of this relationship is a most important step forward. It is, in any case, basal to further investigation, but its significance may be differently interpreted.

In the main, Ruedemann has adopted the general philosophy of earth deformation advocated by T. C. Chamberlin, which is the basis also for the present paper. His great assemblage of data and deductions from them help support that philosophy, while those theories help explain the observed facts. But while strongly in accord with most of Ruedemann's contentions, the present writer would venture to place the emphasis somewhat differently in some respects and to see a different significance in several of the conclusions.

Ruedemann finds the pre-Cambrian trend lines of North America and Eurasia in general parallelism to the borders of these continents, but apparently does not believe that a similar relationship holds for South America, Africa, and Australia. Perhaps he has felt obliged to take cognizance of the hypothetical Gondwanaland instead. On his chart (Fig. 1) appears Archi-Gondwana, a continental mass extending from Brazil to Australia and including the Indian Ocean, all of Africa except Cape Colony, and much of the South Atlantic. The trend lines throughout this great area are drawn north and south. Because the structural lines are observed to be dominantly north and south in the widely scattered regions of Africa, Madagascar, India, and Western Australia, it is argued that in pre-Cambrian times these scattered areas were all parts of a single great continent which deformed as a unit with similarly oriented lines of folding throughout. This conclusion in an otherwise logical paper seems to the writer as extraordinary as most of the other arguments in favor of the supposed Gondwanaland which abound in the literature. Assuming that Archi-Gondwana did exist as drawn, its long dimension and its longest coasts lie in an east and west direc-

[1] *Op. cit.*, pp. 112–16.

tion and more folding should be expected along east and west axes than along north and south. The same north and south trend in all parts of the vast area is just what should not occur. Ruedemann's chart shows vividly how sharply the supposed Gondwanaland is in contrast to the other continents. It is in direct opposition to the general principles so well stated by Ruedemann himself. Instead of one steady direction of folding throughout, the structural lines should be sweeping curves bearing some relation to the borders of the land mass. The trend lines do not harmonize with the conception of Gondwanaland.

But instead of going so far out of the way to combine three widely separated continents and two ocean basins into one great continent, one may ask whether the observed structural lines will not fit more naturally into the framework of the present continents, South America, Africa, and Australia. The answer seems to be: They will. In South America the dotted lines of post-Proterozoic folding in the pre-Cambrian rocks (in part probably of posthumous character, according to Ruedemann) block out with great fidelity the present pear-shaped continent. The only exception is the change in the stem to the south. Africa resembles somewhat an Indian arrowhead pointing south. With the Indian Ocean on the east and the Atlantic on the west, the grain of such a mass should naturally follow north and south lines. To be sure, there might be a closer accordance between the structural lines and the details of the curving coasts, but, in the large, the structural pattern is harmonious. The blunt southern tip of the arrowhead (Cape Colony), characterized by east and west foldings parallel to the coast, is so far out of adjustment in Ruedemann's scheme that he has even felt obliged to sever it altogether from Gondwanaland. But assuming that the African continent of earlier times bore a general resemblance to its present configuration, this curving of the folds around the southern end concentric with the coast is precisely as it should be, according to our general proposition. The north and south grain of Madagascar and western Australia are what one would predict on the hypothesis that the directive thrusting came from the Indian Ocean segment. India, however, is more doubtful and will be left as an outstanding feature.

In brief, the framework of each of the present continents appears to have been developed early in geologic history. Changes there have been during long subsequent time, but the identity of the continents seemingly has been maintained. This is little more than reiteration of the doctrine of permanence of continents and ocean basins so admirably stated by Dana sixty years ago[1] but ignored by many leading geologists, particularly in Europe. The switching

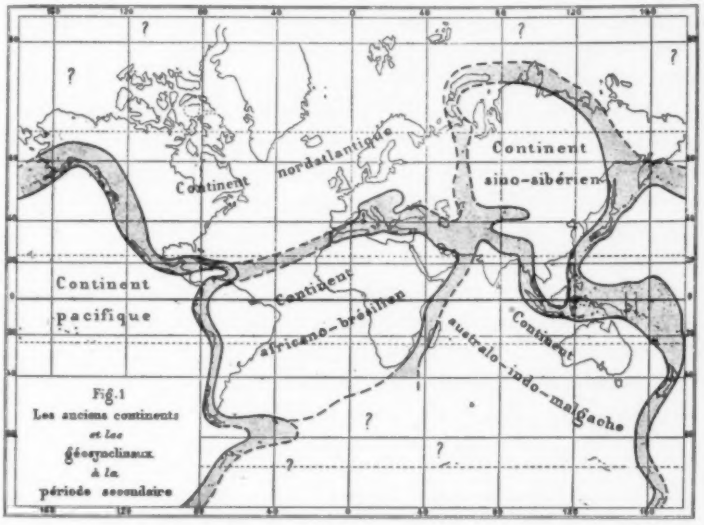

FIG. 3.—The globe divided into continents and geosynclines. (From Haug)

around of continents seems to have an especial appeal to the imagination. One of the most declared cases is the famous work of Haug,[2] whose map for Mesozoic time pictures the surface of the globe as made up exclusively of continents and geosynclines (Fig. 3). The Pacific continent, North Atlantic continent, Africano-Brazilian continent, Sino-Siberian continent, and Australo-Indo-Malgache continent make up the entire surface of the globe, except for narrow,

[1] James D. Dana, *Manual of Geology* (1863), pp. 732–40.

[2] Emile Haug, "Les Géosynclinaux et les Aires Continentales," *Bull. Soc. Géol. de France*, 3d ser., Vol. XXVIII (1900), pp. 617–710, Fig. 1 on p. 633.

tortuous geosynclines between them, and some unknown areas with question marks in the far north and far south. Where are the oceans? And where would the water go? These narrow geosynclines cannot have been deep, for the sediments accumulated in them, wherever visible today, indicate comparatively shallow water, as do also the sediments deposited more widely over the continents in the evanescent epicontinental seas. This well-known diagram makes provision for very little water. It is hard to believe that anything in the sedimentary record or in the migrations of living forms demands any such inversion of the earth's major relief features as this.

Agreeing with Ruedemann's conclusion that the observable grain of the pre-Cambrian structures foreshadows in many particulars the present continents of North America and Eurasia, the writer would extend the generalization also to South America, Africa, and Australia. In each of these masses the early framework is at least consistent with the later development. He would also accept the principle of essential permanence of continents and ocean basins as most conservative, least speculative, and most nearly in accord with the facts. The balancing of the evidence, diastrophic, isostatic, stratigraphic, and paleontologic, is, however, beyond the scope of this paper.

SIGNIFICANCE OF FOLDING ON CONTINENTAL BORDERS

Deformation takes place where the resisting powers of the rocks are overcome. Folding and faulting of the surficial portion of the earth should therefore be located by (1) intensity of the horizontal compressive stress and (2) weakness of materials We have seen that folding in later geologic times has been very prevalent near the continental borders and in so many cases closely parallel with them, and that the later folds have not as a rule departed very widely from the earlier folds, which occupied in many cases very nearly the same areas and had similar trends. The controlling conditions must have occurred largely in these locations and they have recurred from time to time. What does it mean? Either the stresses have been more intense near the continental borders, or the materials there have been weaker, or in a less resisting attitude, or there has been a combination of these.

Intensity of stress.—If the source of lateral thrusting in the earth's outer shell be the rearrangement of matter in the inner earth into denser and more compact forms, the thrusting forces should as a rule develop throughout the outer portion of the globe. If, however, the rearrangement is sometimes local, as it may very well be, a smaller portion of the globe would be involved. With oceanic segments taking the lead in downward crowding, the greatest intensity of thrusting in the average case should be expected in the critical border tracts between oceanic and continental segments. Ordinarily, less intensity of compressive stress should prevail in the interior of the segments, though exceptionally, the greatest intensity might develop elsewhere than on the borders, within either a continental segment or an oceanic segment. Other things being equal, the general result should be greatest deformation in the border tracts.

With each recurring period of diastrophism, the denser ocean segments, further burdened by sediment from the land areas, should sink, and the eroded and lightened continental masses should rise in accordance with the principles of isostasy taken broadly. The areas which were ocean should continue ocean, and the areas which were continental should be re-elevated and restored. Hence the permanence of continents by rejuvenation. Any other concept requires great changes and reversals in the density of the segments which, in a globe of essential solidity, would be a matter of extreme difficulty.

With the continents and oceanic basins remaining in the same general positions throughout geologic time and maintaining relationships probably not varying radically, stresses recurring from time to time should be expected to develop along more or less similar lines. Thrusting should continue greatest on the continental borders. And similar forces should tend to give similar trends to the main lines of diastrophism. Many of the lines of yielding in the later history of the globe should coincide with, or show close relationship to, the lines of yielding of the earlier history. History by repeating the stress conditions repeats the diastrophism.[1]

[1] Too close a parallelism is not to be expected. The condensation in the interior of the earth is a variable; details in the outlines of continents change; and the strength of materials in a given region may change from time to time.

Strength of materials.—The second factor is the strength of materials. Other things being equal, yielding will occur where the resisting strength is least. Low resisting power may be due either to inherent weakness of materials, or to weakness of attitude, a particular border quality. Yielding by folding might be expected in the marginal portion of either an oceanic or a continental segment. But the continents on the wedge principle being pushed up relative to the oceanic segments, though not with respect to the center of the earth, upward relief from horizontal thrusting is easier than relief downward, and crumpling of the borders of the upthrust segment probably easier than corrugation of the sinking segment. Also the materials of the ocean segments are denser and, according to Jeffreys, stronger than the materials of the continents.[1] Therefore, as a general rule, easement of the tangential thrusting would be accomplished more readily by crumpling of the continent rather than the ocean floor. Locally, however, where the oceanic column has been sufficiently weakened by the deposition of sediments to unusual thickness, conditions may be reversed.

Deposition of sediments in exceptional quantity is a means of lessening the resisting powers of an area. On the continents the greatest thicknesses of sediment commonly accumulate near the existing high lands. The destruction of a high mountain range furnishes large quantities of sediment which, if the conditions are favorable, will accumulate in greatest mass on the adjacent lowlands or in adjoining areas of depression. That the strips adjoining mountain ranges very commonly are favorable for deposition seems to be established. The broad, upwarped mountain chain is flanked very commonly, on one side at least, by a corresponding strip in which downwarping prevails—a geosynclinal belt paralleling the upfolded range. We may observe at the present time the Chile Trough, or pronounced fore-deep related to the Andean uplift, the Aleutian Trough lying off the Aleutian uplifted chain; the Japanese Trough off the Japanese chain, the Philippine Trough bordering the Philippines, the Tonga, Kermadec, and New Zealand troughs paralleling these strips of islands, the Sunda Trough off Java and the other Sunda Islands, the deep between the New Hebrides and New Caledonia, as well as various minor deeps in the East Indies and

[1] Harold Jeffreys, *op. cit.*, p. 137.

other archipelagoes. On the present continents are likewise the intermontane valley of Chile, the Gulf of California, and the plains of the Indus and Ganges among the more declared cases. We see, therefore, commonly downwarped or downfaulted troughs bordering the belts of uplift. These constitute a geanticlinal-geosynclinal couple.

In such adjoining troughs sediments from the nearby mountainous belts will accumulate to unusual thicknesses. Soft shales will constitute an important part of the thick deposits. Given sufficient time and occasional rejuvenation of the mountainous strip as it is worn down, with corresponding sinking of the trough, and the latter will be filled to depths of many thousands of feet with relatively weak sediments. This belt of relatively weak rocks, extending to notable depths and growing deeper and deeper, becomes increasingly susceptible to deformation with the renewal of mountain-forming stresses. Joly's principle of further weakening of the rock, in areas of heavy deposition, by heat developed from added radioactive matter in the thickened zone, would increase the susceptibility.[1]

Mountains of the strongly folded and thrust-faulted sort belong to the thin-shelled type, characterized by shallow deformation.[2] In these the thickness of sediments in the ancestral geosyncline from which the mountains arose has amounted to a very appreciable proportion of the total thickness of shell which has undergone active folding, and the resisting powers of the latter in consequence of this high proportion of weak rocks must have been notably diminished.

In addition, Willis has shown that the effects of horizontal thrust tend to be concentrated in zones of sedimentary rocks because stratification facilitates movement between layers and hence folding, and also because the common deflection of such strata from a strictly flat attitude (initial dip) establishes initial lines of flexure. At the same time uplands of erosion and lowlands of aggradation are commonly joined by a monoclinal flexure which becomes an influencing factor in subsequent folding.[3]

[1] John Joly, *The Birth-Time of the World* (1915), pp. 116–45.

[2] Rollin T. Chamberlin, "The Building of the Colorado Rockies," *Jour. of Geol.*, Vol. XXVII (1919), p. 248.

[3] Bailey Willis, *Research in China*, Vol. II, pp. 116–17.

The thick accumulation of weak sediments is thus quantitatively important in locating the belts of strong folding.

These principles are well exemplified in the history of Appalachia and the Appalachian Mountains. Deformation of the Atlantic border of North America from late Proterozoic to late Paleozoic times wrinkled up the land of Appalachia. From what other analogies we have, this land of Appalachia should have been a mountainous belt of average width on the margin of the continent. There is no necessity for postulating half a continent out in the Atlantic. Rather the contrary. Detritus from this range was poured into the Appalachian Trough, which paralleled this chain on the west. As the land was denuded and sentiments accumulated in the trough, the mountainous belt was several times rejuvenated (close of Ordovician, after the Hamilton, and to lesser extents at other times). Meanwhile the trough sank. Finally, by Permian times as much as 30,000, and possibly 40,000, feet of sediment had accumulated in some parts of the trough.

As the maximum depth of folding in the middle of the Appalachian wedge in Pennsylvania is only 32 miles and the folding on the sides is much shallower,[1] 6 or 7 miles of Paleozoic sediments would constitute an important part of the shell-block which was about to be deformed. Previous to the Permian, whenever the compressive stresses became too great to be endured, it was the bordering strip of Appalachia which gave way each time and suffered deformation. This was natural, being nearest the ocean segment where stresses were most intense. But finally, in the closing stages of the Paleozoic, when thrusting was renewed, it was no longer the old strip of Appalachia which yielded, but the weakened sediment-filled Appalachian Trough bordering it on the west. By Permian times this had become sufficiently weaker than the crystalline rock belt of Appalachia that, although these stronger crystalline rocks in the latter area may have been subjected to more intense thrusting, they were better able to resist, and it was in the weaker belt to the west that the thrusts became too great for the rocks to withstand. The relation between strength of materials

[1] Rollin T. Chamberlin, "The Appalachian Folds of Central Pennsylvania," *Jour. of Geol.*, Vol. XVIII (1910), p. 245.

and differential stress was the governing factor. The Appalachian Trough became the Appalachian Mountains and the old highlands of Appalachia were less affected. Since the Appalachian revolution the same belt has undergone recurring uplift, and sediments have accumulated to the east. A migration of belts of mountain folding and a migration of geosynclines is thus suggested as a phenomenon of general occurence.[1]

DEVELOPMENT AND SIGNIFICANCE OF "POSTHUMOUS FOLDING"

The expression "posthumous folding" has generally carried the idea that later lines of folding tend to follow earlier foldings because earlier structural lines, or the grain of a region, constitute lines of weakness (like the grain of wood) which to a considerable extent influence the location and direction of subsequent deformation. Cases where buried tectonic lines have exerted a controlling influence upon newer structures forming in superjacent beds can be cited with confidence,[2] and this must be a factor of some importance in the orientation of mountain chains. But in the larger workings of earth deformation, such as the observed tendency of Paleozoic (and later) trend lines to show so generally a close relation to the pre-Cambrian trend lines, as brought out so well by Ruedemann, the writer would urge the greater importance of the two other factors above outlined.

As already stated, the noted tendency to parallelism of trend lines would therefore be attributed in the first place to the fact that with the major relief features of the globe outlined early, orogenic stresses recurring from time to time should develop along more or less similar, or at least related, lines. Considerable variation, however, might enter from time to time with modified conditions.

In the second place the earlier ranges play an indirect part in the location of later belts of folding through the development of adjoin-

[1] Amadeus W. Grabau, "Migration of Geosynclines," *Bull. Geol. Soc. Amer.*, Vol. XXX (1919), p. 87.

[2] A. E. Fath, "The Origin of the Faults, Anticlines and Buried Granite Ridge of the Northern Part of the Mid-Continent Oil and Gas Field," *U.S. Geol. Survey Prof. Paper 128-C* (1920), pp. 75–84.

W. T. Thom, Jr., "The Relation of Deep-seated Faults to the Surface Structural Features of Central Montana," *Bull. Amer. Assoc. Pet. Geol.*, Vol. VII (1923), pp. 1–13.

ing geosynclines into which are poured great thicknesses of weak sediments from denudation of the mountains. These troughs of deep sediments in their turn finally become the mountain chains of a later generation and by their inheritance tend to be roughly parallel to the ancestral chains.

Thus the framework of the continents is an outgrowth of the special stress conditions developed near the borders of continents. The recurrence of folding and faulting in these situations and the further development of the frame in later ages by the rise of new folded chains in general alignment with the earlier ones results (1) from the natural recurrence of more or less similar stress conditions, particularly in these critical border zones of great segments; (2) from geosynclines bordering early ranges developing weak belts which later, by yielding to the stresses, localize subsequent foldings; and (3) the influence of the earlier structural grain in determining to some extent subsequent yielding.

GENERAL BEARING

These interpretations have assumed the correctness of the doctrine of permanence of continents and ocean basins in its essential features, and are supplementary to that doctrine. But taking the observed facts independently of any theories, we find (1) that the existing mountain ranges, with a few exceptions, are emphatically parallel to the borders of the present continents, and (2) that the trends of the Mesozoic, Paleozoic, and even pre-Cambrian mountain chains, in many cases, are in essential parallelism to the existing ranges and to the existing continental margins. Hence the strong presumption that the Mesozoic, Paleozoic, and pre-Paleozoic folded ranges bore a similar relation, respectively, to the Mesozoic, Paleozoic, and pre-Paleozoic continental borders, and finally that the margins of the continents have not changed in their general positions very profoundly throughout all these ages.

It is generally agreed that the nature of the sedimentary deposits on the continents indicates that they have been deposited in shallow epicontinental seas, and that the present continents have never been depressed to form parts of the deep-sea floor. The countless disconformities throughout the stratigraphic column show how

transient and oscillatory these shallow submergences have been as a rule. Our continental areas have been continental areas from very early times. Nor will it do to fill up the ocean basins with additional continents as so many have delighted in doing, for the water must go somewhere, and there is no apparent reason why the ocean-basin areas should change their essential characteristics any more readily than the continental areas.

The framework of the continents corroborates the testimony of the sediments that our present continents are very ancient. It also supplements the evidence from the sediments in shedding further light upon the general outlines of the continents at various times in geologic history. The framework, in the opinion of the writer, ought to make it possible to affirm the presence of ocean basins at certain times in certain debated parts of the globe with much confidence. For example: The Taconic, Shickshockian, and Appalachian folded ranges point strongly to a bordering Atlantic lying at no very great distance to the eastward at the times when these ranges were folded. Similarly, the Serra do Espinhaço, folded and faulted in pre-Devonian time, and now paralleling the coast of Brazil so faithfully, strongly suggests that the South Atlantic Ocean Basin lay in pre-Devonian times about where it does today. This argument has already been used against the practice of running a land mass (Gondwanaland) from Brazil across the Atlantic Basin to Africa in Paleozoic and Mesozoic times.[1] In the same way ancient trend lines in Africa and Australia are more consistent with the present distribution of continents and ocean basins than with any such radical modification as Gondwanaland postulates.

In conclusion, the system thus outlined advocates the essential permanence of continents and ocean basins. It allows only moderate and conservative modifications of the earth's major relief features where the evidence unmistakably calls for very definite modification. Postulated continents out in the present ocean basins, like Gondwanaland, Atlantis, Eria, and various others, form no part of this system. It is believed that the ancient structural trend lines, in conjunction with the distribution, thicknesses, and

[1] See review of "Harvard Geological Expedition to Brazil and Chile, 1908–9," *Jour. of Geol.*, Vol. XXI (1913), p. 285.

general nature of the sedimentary deposits, afford by far the best evidence known at present for delineating the continents and oceans of the past. And that, just as the volcanic islands springing up in the mid-Pacific today quickly become jungle-covered without a thousand miles of land tying them to a continent, so it is believed by the writer that, in explaining the peculiarities of life-distribution, much more may be left to the traveling capacities of the plants and animals themselves than has sometimes been done, and that tectonic and sedimentary evidence should not be brushed aside lightly unless all other explanations are tried and found wanting.

MARINE INVERTEBRATE FOSSILS AS HORIZON MARKERS IN THE PENNSYLVANIAN ROCKS OF ILLINOIS

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ABSTRACT

It has generally been assumed that the marine invertebrate fossils occurring in the rocks of the Pennsylvanian system have such a great vertical range that the species are of no value as markers of particular formations within the system. The purpose of this paper is to call attention to the fact that while many of the marine species found in these rocks in Illinois do range through a great vertical thickness, a number of the species are so restricted in their range that they are diagnostic of a single formation, or of a narrow horizon within a formation. Also there are other species that may occur in more than one formation, but their shells are present in great numbers only in a single formation so that even these can be used in the recognition and correlation of the subdivisions of Pennsylvanian rocks in this state.

There is a rather widespread impression that the fossil species of marine invertebrates occurring in the Pennsylvanian rocks range generally throughout that system, and that certain species are not so restricted in their vertical range that they can be used as guides to its different divisions or formations. This general impression has resulted in part from the lack of thoroughness in the collection and study of these fossils, so that the vertical range of the different species could actually be determined. The importance of these fossils was neglected in the early study of the Pennsylvanian rocks because, in the Appalachian region where these strata were first studied in this country, the sediments are mostly of continental origin, and marine fossils are not common.

During the progress of the investigations of the First Geological Survey of Illinois, Worthen referred to the Pennsylvanian, or coal-bearing, rocks of the state as the "Coal Measures," and divided them into the Lower and Upper Coal Measures, the separation being made at the Carlinville limestone. He also assigned consecutive numbers to the more important coal beds, beginning with Number 1 at the bottom, up to and including Number 16 at the top.

The coal-bearing rocks of similar age in Pennsylvania and the Appalachian basin had been studied in detail some years earlier on account of the economic importance of the coal in the development of the country. Because the sediments of this system in the East were mostly of continental origin and horizons containing marine invertebrate fossils were rare, the subdivision of the system into formations was there based upon the plant fossils, rather than upon the marine invertebrate fossils, which furnish the most dependable and important criteria for the correlation of the older Paleozoic formations.

In Illinois and the Eastern Interior basin the sediments making up the Coal Measures are largely marine, and marine invertebrate fossils occur in abundance at many different horizons. However, a large number of the more common species do range throughout the entire thickness of the Coal Measures, and during the First Geological Survey the marine fossils had not been collected and studied with sufficient care to determine definitely the vertical range of the different species. Consequently it was impossible to tell what species, if any, were restricted to particular horizons, so that they could be considered diagnostic of definite levels in the Coal Measures.

Soon after the present Illinois State Geological Survey was organized, plans were made to determine whether the strata of the Coal Measures in Illinois could be definitely correlated with those of corresponding age in the Appalachian basin. Inasmuch as the subdivisions of these rocks in the latter area had been largely made on the basis of the plant fossils, the help of the eminent paleobotanist, Dr. David White, who had been the chief student of the plant fossils in the eastern basin, was secured for studies in Illinois. As a result of these studies he attempted the general correlation of the Pennsylvanian strata in the two regions.

Dr. White[1] concluded, more or less tentatively, that all of the rocks of the Pennsylvanian system in Illinois below the Number 2 coal bed were about equivalent in age to those of the Pottsville formation of the Appalachian region. He thought that the strata between and including the Number 2 and Number 6 coal beds

[1] David White, *Ill. State Geol. Surv. Bull. No. 14* (1909), pp. 293–95.

were less certainly, but approximately, equivalent to the Allegheny formation of the East; and that the Pennsylvanian rocks above coal Number 6 were post-Allegheny in age.

In conformity with these determinations a beginning was made in 1910 to subdivide the Coal Measures of Illinois, and to assign locality names to these divisions[1] as follows:

The name Pottsville formation was proposed to include all of the Pennsylvanian rocks in the state below the Number 2 coal bed. The LaSalle formation was defined to embrace the strata between the base of the Number 2 coal and the base of the Number 5 coal bed. In conformity with the usage by the United States Geological Survey in the Ditney, Indiana, Folio, the strata between the base of coal Number 5 and the top of coal Number 6 were assigned to the Petersburg formation. All of the Coal Measure strata above the top of the Number 6 coal bed were included in the McLeansboro formation, the name being taken from the county seat of Hamilton County, where a well-boring showed that the thickness of these strata exceeds 1,000 feet.

Some uncertainty soon arose with regard to the exact correspondence of the strata included in the Petersburg formation, as defined in Illinois, with those referred to the formation bearing this name in Indiana, and it was thought best in 1912 to combine the LaSalle and Petersburg formations, as defined above for Illinois, under the name Carbondale[2] formation, from the town of Carbondale in Jackson County. With this change the formation subdivisions of the Coal Measures in Illinois became substantially as at present.

In view of the fact that the invertebrate marine fossils have been universally recognized as the most reliable and best possible means of recognizing and correlating the formations of the Paleozoic rocks older than the Pennsylvanian, the writer undertook the thorough and systematic collection and study of marine fossils from the successive strata of the Pennsylvanian system in the state in

[1] F. W. DeWolf, *ibid.*, No. 16, pp. 180–81; and T. E. Savage, *ibid.* (1910), pp. 271–74.

[2] E. W. Shaw and T. E. Savage, "Description of the Murphysboro-Herrin Quadrangles," *U.S.G.S. Folio No. 185* (1912), p. 6; also E. F. Lines, *Ill. State Geol. Surv. Bull. No. 17* (1912), p. 74.

an effort to determine the vertical range of the species, and so to discover those that are restricted to a rather narrow vertical range. This study is not yet completed, but sufficient information has been obtained to justify the following preliminary statement of results.

Certain species of these fossils have been found to be diagnostic of certain horizons, so that they can be safely used as guides to the different formations of the Pennsylvanian, just as in the older systems of Paleozoic rocks.

As far as now known in Illinois, the following species have not been found above the Pottsville formation, and hence can be considered as definitely identifying this lowest division of the Pennsylvanian system as at present defined.

SPECIES OF FOSSILS RESTRICTED TO THE POTTSVILLE FORMATION IN ILLINOIS

Chainodictyon laxum var. *minor* Ulrich
Cystodictya carbonaria (Meek)
Diploporaria biserialis (Ulrich)
Fenestella delicatula Ulrich
Fenestella mimica Ulrich
Fenestella perminuta Ulrich
Fenestella sevillensis Ulrich
Fenestella wortheni Ulrich
Pinnatopora bellula Ulrich
Polypora whitei Ulrich
Rhombopora multipora Foerste
Septopora delicatula Ulrich
Marginifera muricata var. *missouriensis* Girty
Thamniscus sevillensis Ulrich
Spirifer boonesis Swallow
Spirifer opimus Hall (cf. *S. rockymontanus*) Marcou

Above the roof shale overlying coal Number 2, there is a marked erosional unconformity in Fulton County, and in other localities in Illinois, and it is possible that further study will prove that this plane of unconformity will be the proper place to make the upper limit of the Pottsville.

In the Carbondale formation, as now limited, the number of known diagnostic species is not so large, but the following are thought to be restricted to this formation in Illinois.

GUIDE FOSSILS TO THE CARBONDALE FORMATION IN ILLINOIS

Chonetes mesolobus var. *euampygus* Girty
Spirifer fultonensis Worthen
Aviculopecten rectilaterarius Cox
Entolium aviculatus (Swallow)

The species *Pugnax rockymontana* Marcou and *Rhynchonella illinoisensis* Worthen appear first in the calcareous shale overly-

ing the Springfield (No. 5) coal bed. They are not known below that horizon, but they may possibly reappear at a higher level. The above-mentioned species would still be restricted to the Carbondale formation if the lower limit of that formation should be drawn at the plane of marked unconformity above the roof shale of the Number 2 coal bed mentioned above.

There is another profound erosional unconformity present in the Pennsylvanian rocks of Illinois several feet above the Herrin (No. 6) coal bed which may in the future be shown to be the proper place to make the separation between the Carbondale and the McLeansboro formations. If the top of the Carbondale formation were drawn at this unconformity, two additional species could be included among the guide fossils of this formation, viz., *Cryptacanthia compacta* and *Strophostylus peoriensis*. These appear first in the calcareous shale above the Springfield (No. 5) coal, and are also found in the strata above the Herrin (No. 6) coal bed.

Within the Carbondale formation there is another erosional unconformity beneath the sandstone underlying the Herrin coal bed and above the shale overlying the cap rock of the Springfield (No. 5) coal bed. This unconformity is of less magnitude than the one just mentioned above the Herrin coal, but it lies at the base of the great overlap of the Herrin coal, and its limestone cap rock in the western part of the state.

The rocks of the McLeansboro formation contain many excellent diagnostic fossils that are not known to occur at any lower horizons in the state. The following are a few of the more important guide fossils to the McLeansboro formation in Illinois:

SPECIES OF FOSSILS CONFINED TO THE McLEANSBORO FORMATION IN ILLINOIS

Syringopora multattenuata McChesney
Erisocrinus conoideus Meek and Worthen
Cromyocrinus sangamonensis Meek and Worthen
Enteletes hemiplicata Hall
Marginifera lasallensis (Worthen)
Macrodon delicatus Meek and Worthen
Sedgwickia topekensis Shumard
Astartella varica McChesney
Yoldia knoxensis McChesney
Conocardium obliquum Meek and Worthen
Myalina perattenuata Meek and Hayden
Myalina recurvirostris Meek and Worthen
Myalina subquadrata Shumard

Myalina swallovi McChesney
Aviculopecten hertzeri Meek
Aviculopecten interlineatus Meek and Worthen
Deltopecten mccoyi Meek and Hayden
Placunopsis carbonaria Meek and Worthen
Pleurophorus subcostatus Meek and Worthen
Loxonema scitulum Meek and Worthen
Pleurotomaria carbonaria Norwood and Pretten
Pleurotomaria spironema Meek and Worthen
Pleurotomaria subscalaris Meek and Worthen
Euconospira turbiniformis (Meek and Worthen)
Goniospira lasallensis (Worthen)
Worthenia tabulata (Conrad)
Worthenia speciosa (Meek and Worthen)
Porcellia peoriensis Worthen
Soleniscus typicus Meek and Worthen
Temnocheilus latus Meek and Worthen
Metacoceras sangamonensis Meek and Worthen

From the foregoing lists of fossils that are thought to be restricted to a single one of the formations of the Pennsylvanian system, it will be seen that the number of invertebrate species that can be used as trustworthy guides to the different divisions of this system compares favorably with the number that are diagnostic of the different formations of the Mississippian, or of the older Paleozoic systems.

A few of the above-mentioned species that are restricted in their range to a single formation are found throughout a thickness of only a few feet, and hence they mark definite horizons within the formation. Among such species, *Chonetes mesolobus* var., *euampygus* and *Spirifer fultonensis* are known to occur only in the upper part of the Carbondale formation, between the Springfield (No. 5) and the Herrin (No. 6) coal beds. The following species are also thought to be restricted in their range to that part of the McLeansboro formation below the LaSalle limestone, *Yoldia knoxensis*, *Bellerophon stevensianus*, *Pleurotomaria carbonaria*, *Worthenia speciosa*, *Porcellia peoriensis*, and *Metacoceras sangamonensis*. Among those that are known in the state only from the LaSalle limestone and higher strata are *Marginifera lasallensis*, *Allerisma granosum*, *Pinna peracuta*, *Euconospira turbiniformis*, *Goniospira lasallensis*, and *Griffithides scitulus*.

Besides those species which are entirely restricted to a single formation or to part of a formation, there are others that still may be very useful in stratigraphic studies. These are forms that occur in so much greater numbers in one formation than in any other that

their presence in abundance may serve often to mark definite formations or to distinguish certain horizons within a formation. Among such species may be mentioned *Girtyina ventricosa*, which occurs in great abundance only in the limestone cap rock above the Herrin (No. 6) coal bed. *Chonetes mesolobus* and *Marginifera muricata* are present in large numbers only in strata older than the McLeansboro formation. In like manner, shells of *Riphidomella pecosi*, *Chonetes granulifer*, and *Trepospira sphaerulata* are very common only in the strata belonging to the lower half of the McLeansboro formation.

A recent paper by Dr. Girty[1] discussing the "Invertebrate Paleontology of Missouri" makes it possible to carry a preliminary correlation of the formations from Illinois west into Missouri, and Dr. Beede's[2] work in Kansas furnishes data for continuing the correlation into that state. A comparison of the vertical range of the Pennsylvanian invertebrate species in Illinois and Missouri indicates that the Pottsville formation of Illinois corresponds in general with the Cherokee shale of Missouri, such characteristic species as *Marginifera muricata* var. *missourienis* and *Spirifer opimus* (near *S. rockymontanus*) being common to both formations. It seems probable that the upper part of the Cherokee formation in Missouri is younger than the youngest Pottsville of Illinois as now defined. The Upper Cherokee shale seems to include strata equivalent to those in the lower part of the Carbondale formation in Illinois. This is indicated by the presence in the Cherokee shale of such species as *Pugnax rockymontana*, *Aviculopecten rectilaterarius*, and *Euchondria neglecta*, which in Illinois are not known below the Carbondale. The names of *Chonetes mesolobus* var. *euampygus* and *Cryptacanthia compacta* appear in Girty's lists as characteristic of the Henrietta formation, and since these species are not known in Illinois below the middle of the Carbondale, it is thought that the Henrietta formation of Missouri corresponds, in general, to at least the upper half of the Carbondale formation. The other Pennsylvanian formations in Missouri appear to be

[1] George H. Girty, "The Stratigraphy of the Pennsylvanian Series," chapter on "Invertebrate Paleontology," *Mo. Bur. of Geology and Mines*, Vol. XIII (2d series; 1915); pp. 263–375.

[2] J. W. Beede, "Carboniferous Invertebrates," *Univ. of Kansas Geol. Surv.*, Vol. VI (1900), pp. 3–187, and other papers.

younger than the Carbondale of Illinois, but it would not seem wise at present to attempt to correlate these subdivisions in detail. It might be suggested, however, that the Kansas City and Lansing formations in Missouri may possibly correspond more or less closely to the Lonsdale limestone and LaSalle limestone, respectively, in Illinois.

Recent papers by Raymond,[1] in Pennsylvania, Price,[2] in West Virginia, and Morningstar,[3] in Ohio, have laid a good foundation for the future correlation of the Pennsylvanian formations between Illinois and the Appalachian basin notwithstanding the relatively few horizons in which marine invertebrate fossils occur in the latter region. In the papers by Raymond and Price, *Thamniscus sevillensis* and *Spirifer opimus* (near *S. rockymontanus*) are listed as persisting into the lowest member of the Allegheny formation, while in Illinois those species are confined to the Pottsville. The presence in the Allegheny formation of the Appalachian region of species which in Illinois are not known to occur above the Pottsville, as now defined, suggests a probability that the upper boundary of the Pottsville formation in the two regions is not now drawn at a corresponding level. Further detailed information of the range of the species in these areas will make it possible to adjust the inconsistencies in the subdivisions that now exist.

In continuing this work the writer is confident that the marine invertebrate fossils will eventually furnish much the best possible criteria that can be used in making the subdivision and correlation of Pennsylvanian rocks, not only in Illinois, but between this state and other regions. When the details of the distribution and range of the different species are quite fully known, it will also be possible to determine what adjustments should be made in the subdivisions and boundaries of these formations in view of the widespread erosional unconformities that are known to be present within this system.

[1] Percy E. Raymond, "A Preliminary List of the Fauna of the Allegheny and Conemaugh Series in Western Pennsylvania," *Annals of Carnegie Mus.*, Vol. VII (1910–11), pp. 144–58.

[2] W. Armstrong Price, "Fossil Fauna of the Conemaugh Rocks," *West Va. Geol. Surv.* (1914), pp. 472–553. "Notes on the Pal. of Kanawha County, *ibid.*, pp. 639–55. See also notes on "Pal." in *West Va. Geol. Surv. Repts. for 1915, 1916, and 1920.*

[3] Helen Morningstar, "Pottsville Fauna of Ohio," *Geol. Surv. of Ohio* (4th series; 1922), Bull. No. 25.

INTRENCHED AND INCISED MEANDERS OF SOME STREAMS ON THE NORTHERN SLOPE OF THE OZARK PLATEAU IN MISSOURI

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ABSTRACT

The streams of the northern Ozark area in central Missouri are well-known examples of intrenchment. The question arose years ago as to whether this intrenchment was due to downward cutting following rejuvenation by uplift or to downward-lateral cutting. Evidence is given to show that the Osage, Gasconade, and Meramec rivers intrenched themselves by downward cutting only as the area over which they were flowing was uplifted, probably in late Tertiary times. Hinkson Creek, a smaller stream, has cut downward and laterally in intrenching itself, being controlled in its downward-lateral cutting by the downward cutting of the Missouri River into which it empties.

INTRODUCTION

The streams flowing across the northern part of the Ozark Plateau have notably sinuous courses, which occupy valleys that are narrow and steep-sided, paralleling the streams closely. The valley bottoms of such major streams as the Osage and Gasconade lie from 100 to 300 feet below the upland surface. The tributaries also occupy narrow, steep-sided, V-shaped valleys, the larger ones having meandering courses and the smaller ones fairly straight courses.

The surface of the northern part of the old upland slopes from its highest points in Wright, Texas, and Dent counties in the central Ozarks to the northwest, north, and northeast. The course of the Missouri River lies across the northern flank of this upland, the northern margin of which is found a limited distance to the north of the Missouri River, crossing Boone, Callaway, and Montgomery counties.

During the early nineties the cause of the intrenchment of these streams was discussed by Professor W. M. Davis[1] and Arthur

[1] W. M. Davis: *Science*, Vol. XXI (1893), pp. 225–27; Vol. XXII (1893), pp. 276–79.

Winslow,[1] then state geologist of Missouri. Professor Davis suggested that the streams had been meandering on a peneplain which had been uplifted, the meandering streams intrenching themselves as the land mass came up. Winslow, although not entirely disagreeing with Davis, suggested that the intrenched streams started as streams with minor sinuosities, and that as they cut downward they cut laterally also, thus increasing the sinuosities to their present size. The essentially horizontal character of the formations constituting the Ozark area favored, he thought, the downward and lateral movement.

Actually, both Davis and Winslow were describing intrenchment, but of two distinct types. The view of Davis is the accepted interpretation of intrenched meanders. They are due to downward cutting in a stream's channel, through rejuvenation, which preserves the original meanders. Winslow's view represents incised meanders, in which the stream has not only gone down but enlarged the meanders by cutting laterally. This important distinction has been very clearly and forcibly developed by Professor Davis in a later paper,[2] but unfortunately for clearness in the use of the two terms the distinction has been lost sight of in recent textbooks and articles on streams. Inasmuch as nothing has been offered to replace the original meaning of "incised" it is strongly urged in this paper that the term "intrenched" be used only for streams that lower their channels vertically, and "incised" be used for those meanders which cut both vertically and laterally.

The derivation of the two words is in strict accord with the meanings given above, as intrench means to protect by means of a trench or wall and incise means to cut into.

It is the purpose of this paper to present the results of some years of study of the meanders of the streams in the northern Ozark area and to show that both types of meandering are present. Winslow was wrong, however, in assuming that the Osage and other streams were incised. Excellent examples of each type are found

[1] Arthur Winslow, *Science*, Vol. XXII (1893), pp. 31–32; Vol. XXIII (1893), pp. 152–53.

[2] "Incised Meandering Valleys, *Phila. Geog. Soc. Bull.*, Vol. IV (1906), No. 1, pp. 1–11.

in this area and will be described. A small stream in Boone County, Missouri, illustrates an incised meander splendidly, and the Osage, Gasconade, and Meramec illustrate intrenched meanders.

GENERAL GEOLOGY OF THE AREA

The formations of the area range from Upper Cambrian to Pennsylvanian in age. The following columnar section shows these formations:

Pennsylvanian	Cherokee shales
Mississippian	Osage
	Kinderhook
Ordovician	St. Peter sandstone
	Jefferson City sandstone
	Roubidoux sandstone
Cambrian	Gasconade

The streams are working primarily on the Ordovician and Cambrian formations. These consist of dolomites and sandstones with minor beds of shale. Dolomite predominates over the other rocks, constituting 80–90 per cent. The dolomite contains a large amount of chert, which constitutes the major part of all the gravel and sand transported by the streams.

The formations underlying the Ozark Plateau are nearly horizontal throughout the area. Actually they dip a few feet per mile to the northwest, north, and northeast in the respective parts of the area. This dip is so slight as to have no influence upon the streams of the area.

Minor faults occur, but neither the few faults nor the joints are prominent enough to have any influence on the position of the valleys, as was suggested by Winslow.[1]

INCISED MEANDERS OF HINKSON CREEK, BOONE COUNTY, MISSOURI

Hinkson Creek, in Boone County, on the north side of the Missouri River (Fig. 1), but still on the northern flank of the Ozark Plateau, shows excellent incised meandering.

The Hinkson is about 25 miles long. It rises in the north central part of Boone County, flows slightly west of south for about

[1] *Op. cit.*

16 or 17 miles to a point near Columbia, then turns nearly west and joins Roche Perche Creek, which flows southwest for about 3 miles to the flood plain of the Missouri River, then, turning abruptly to the southeast, flows along the flood plain for 4 miles before joining the Missouri. Both the Hinkson and Roche Perche meander, more or less, but the portion of the Hinkson's course from a point just east of Columbia to 2 miles southwest of Columbia has

FIG. 1.—Physiographic provinces of Missouri and the streams discussed in this paper.

well-developed incised meandering. This portion of the stream is shown on the accompanying figure (Fig. 2). The valley is cut in the Burlington limestone in this portion while that to the northeast is cut in soft Pennsylvanian shales and limestones and is many times wider than the portion cut in the Burlington.

The actual length of the stream in the area figured is nearly twice the airline distance and includes several interesting drainage changes. Before describing these changes it should be noted

that this area was covered by the ice during the glacial period and that the present valley of the Hinkson has been, in major part at least, developed since the retreat of the Kansan ice sheet. The area to the south of the river was not covered by the ice. This

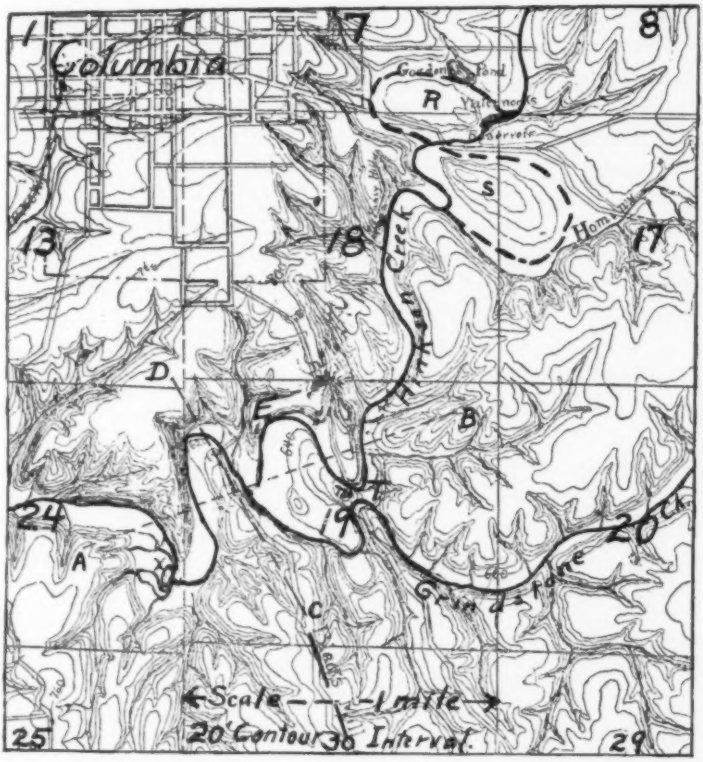

FIG. 2.—Incised meanders of Hinkson Creek, near Columbia, Boone County, Missouri.

glaciated area was a nearly level surface which sloped mainly to the south in the north central and northwestern parts of Missouri, as is shown by the straight southward courses of the streams of northern Missouri (Fig. 1).

The present valley of the Hinkson, then, is a measure of the erosive work of a small stream since the time of the Kansan ice sheet. It has developed a valley, which, when the respective volumes of the streams are considered, is on a par with that of the much larger Osage and Gasconade rivers.

Examining the course of the Hinkson, as shown in Figure 2, two relatively sharp meanders occur in the northeast quarter of Section 18, just below the old waterworks reservoir. Just to the west of the reservoir lies a small hill *R*, surrounded by a shallow valley. Gordon's Pond is the result of damming up a portion of this valley.

The Hinkson formerly occupied this valley, which may have been preglacial, but not necessarily so, as is shown by the equal development of similar meanders in limestone, a mile or so downstream. (The former course of the stream is shown by the heavy dotted line in Figure 2.) The hill *R* was formerly part of an upland spur projecting into the meander of the stream. The stream impinged against the north side of the spur, swung around its west end, and continued on to the southeast around hill *S*. Eventually it cut through the spur *R*, mainly from the upstream side, and isolated hill *R* by abandoning its former course. This is an example of "planation stream piracy" as described by Malott.[1] It may have been aided in cutting through by an underground solution channel as has been found to be the case by J. Bridge[2] for several Ozark streams.

The narrow opening through the spur, having rock bluffs on both sides, furnished an excellent site for a dam and was so used by the old Columbia waterworks company.

Hill *S*, 60 feet high, is entirely surrounded by a shallow valley and was the former course of the Hinkson as noted above. Only part of the valley is occupied by an active stream at present. The steep slope (Fig. 2) at the northwest end, opposite the high bluff on the west side of the Hinkson, shows that this hill is also a cut-off portion of an upland spur. The stream, after cutting through the

[1] Clyde A. Malott, "Planation Stream Piracy," *Proc. Indiana Academy of Science* (1920), pp. 249–60.

[2] Personal information.

upland spur *R* and isolating hill *R*, impinged sharply against the side of upland spur *S*, then turned southeast and flowed around hill *S* and again cut into the upland spur on its lower side, soon cutting through and isolating hill *S*. The relationship of the bluffs on the present and former streams suggests that an underground channel aided in making this cut-off. It must have occurred soon after the first, if width of valley can be used as a measure of the time. Davis[1] has described the same type of cut-off on the Moselle near Berncastel, Germany.

Farther down the stream in Sec. 19, T. 48 N., R. 12 W., and Sec. 24, T. 48 N., R. 13 W., the Hinkson has developed five strong

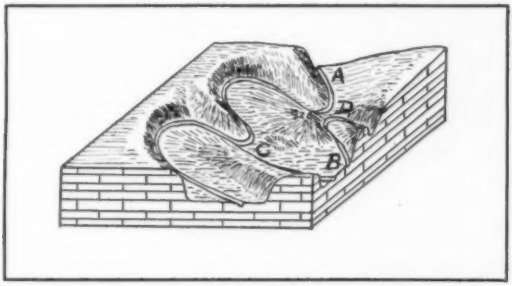

FIG. 3.—Stereogram showing incised meanders of Hinkson Creek, Boone County, Missouri. *A*, Hinkson Creek; *B*, Grindstone Creek.

meanders in a distance of 1 mile. Each meander surrounds an upland spur, from 80 to 120 feet high, having a nearly vertical face on the upstream side and a gently sloping face on the downstream side, unless the meanders have cut in so close on that side as to steepen them (Fig. 3). The small isolated hill (Fig. 3) on the flood plain in Section 19, between the Hinkson and its tributary, the Grindstone, was formerly a part of the hill *E* and was isolated by the same method as hill *R*. There is also the possibility that this hill may have been the result of side cutting by the foregoing streams as is illustrated by the present development of "hill 720" (Fig. 3). The close approach of these two streams at the point *D* has nearly cut off this hill. Had this occurred, as it will in time, the Hinkson

[1] "The Seine, the Meuse, and the Moselle," *Nat. Geog. Mag.*, Vol. VII (1896), p. 193.

would have acquired the headwaters of the Grindstone and would have perpetuated an interesting case of piracy through lateral planation.

The last prominent meander of the Hinkson as shown on Figure 2, in the east part of Section 24, has shortened itself and left a low hill on its flood plain at the point marked *x*. This hill was once a part of the prominent hill to the north (known locally as Lover's Leap). All of these small isolated hills consist of the same stratified Burlington limestone (Mississippian) as that forming the bluffs on the stream, thus furnishing further proof that they were originally parts of the surrounding upland.

There are remnants of several flood-plain terraces to be found all along the course of the stream. The interval between terraces ranges from 3 to 20 feet. The highest terrace, of which only small patches remain, is some 40 feet above the living flood plain of the Hinkson. The more recent downward movements have usually been 3–8 feet.

HISTORY OF THE HINKSON'S DEVELOPMENT

The ice sheet left this area essentially flat. Preglacial valleys existed, but were filled with glacial drift. One preglacial valley, about a mile and a half north of the area shown in Figure 2, contains about 100 feet of drift and had an east and west course. The Hinkson's present valley cuts across this old preglacial valley.

Any stream flowing away from the front of the ice sheet would develop its valley by taking advantage of such irregularities as existed on the surface of the drift. The little topographic evidence available along the Hinkson indicates that it probably had a course marked by more or less irregularity. Downward cutting was controlled by the level of the Missouri River into which the Hinkson emptied. For a time after the retreat of the ice, the Missouri was evidently overloaded with débris from the melting ice and had aggraded its channel to a considerable height above its present level. The rock bottom of the Missouri may also have been at a higher level. That the water stood at a higher level than at present is shown by the occurrence of glacial bowlders along the Osage River and some of its larger tributaries at elevations ranging from 25 to 75 feet above the present river. Their position has been explained

as due to ice floating up the streams which evidently contained much backwater from the melting ice. The bowlders at the lower levels may, of course, have been let down through erosion, but those at higher levels show that the water was either very deep in these streams or that their bottoms were at higher levels.

In view of the long period of time that has passed since the Kansan ice sheet was in this vicinity, 300,000 to 1,000,000 years ago, it would seem reasonable to conclude that the Missouri River had lowered its rock bottom to some extent. The river valley contains from 25 to 100 feet of valley fill at present. A conservative estimate of this lowering might be 25 feet, with 50 feet still within the range of probability. At any rate, the evidence all indicates that the Hinkson entered the Missouri River at a higher level during its early history.

Any lowering of the Missouri River level would be reflected in the lowering of the channels of its tributaries. During the early history of the Hinkson it would be cutting into the relatively soft glacial material, but would soon encounter, especially in its lower course, the underlying Burlington limestone. Throughout its history, the Hinkson has been retarded in its downward cutting by the slower downward cutting of the Missouri River, which forced the Hinkson to cut laterally as well as downward. Its cutting was facilitated by the nearly horizontal dip of the Burlington limestone, which permitted horizontal sapping at the foot of any cliffs developed, and an abundance of tools, derived from the drift in part, but largely from the Burlington limestone, which contains an abundance of chert that readily breaks up into sharply angular tools well suited for abrasion. Corrosion was also undoubtedly very effective in removing material.

The downward-lateral movement widens the meander at its end and on the downstream side, thus undercutting the upstream side of the upland spur. As a result the entire meander belt is shifting downstream. This lateral-downward movement develops the slip-off slopes, shown in Figures 3, 4, and 5, and profile *A*, Figure 6. Slip-off slopes are always an accompaniment of *incised meanders*. Figures 4 and 5 show the probable successive positions of the stream in developing its incised meanders. That these are incised meanders is shown by the valley walls not being equally

steep on both sides and by the long gentle slopes on the ends and downstream slope of the upland spurs, which project into each meander as they do in normal intrenchment. The development of its incised meanders by the Hinkson has taken place without the aid of upward movements of the land mass, but by the slow lowering of its outlet. This type of incised meander would develop best under the conditions of static rejuvenation as described by Malott.[1]

FIG. 4.—Profile along a slip-off slope showing, *a*, *b*, *c*, and *d*, successive positions of the Hinkson during its development.

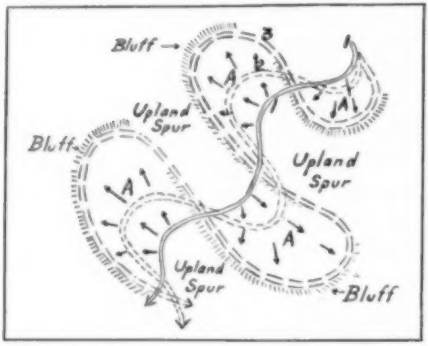

FIG. 5.—Plan, showing the shifting of the meanders and the development of upland spurs with the bluffs facing upstream and slip-off slopes facing downstream—the direction of migration of the meanders. (1) Early course of the Hinkson. (2) Intermediate course. (3) Present course.

Conclusion.—Hinkson Creek furnishes an excellent example of "incised meanders," caused by the downward-lateral cutting of the stream as its outlet stream, the Missouri River, was lowered. During this incising the Hinkson intrenched itself from 80 to 120 feet below the surrounding upland, and developed overlapping

[1] "Static Rejuvenation," *Science*, Vol. LII (1920), pp. 182–83.

upland spurs which have a steep bluff facing upstream, a long gentle slope on the back, and another leading down to the apex of the meander, the "slip-off slope," formed as the stream slid down the back and end of the overlapping upland spur. The Hinkson

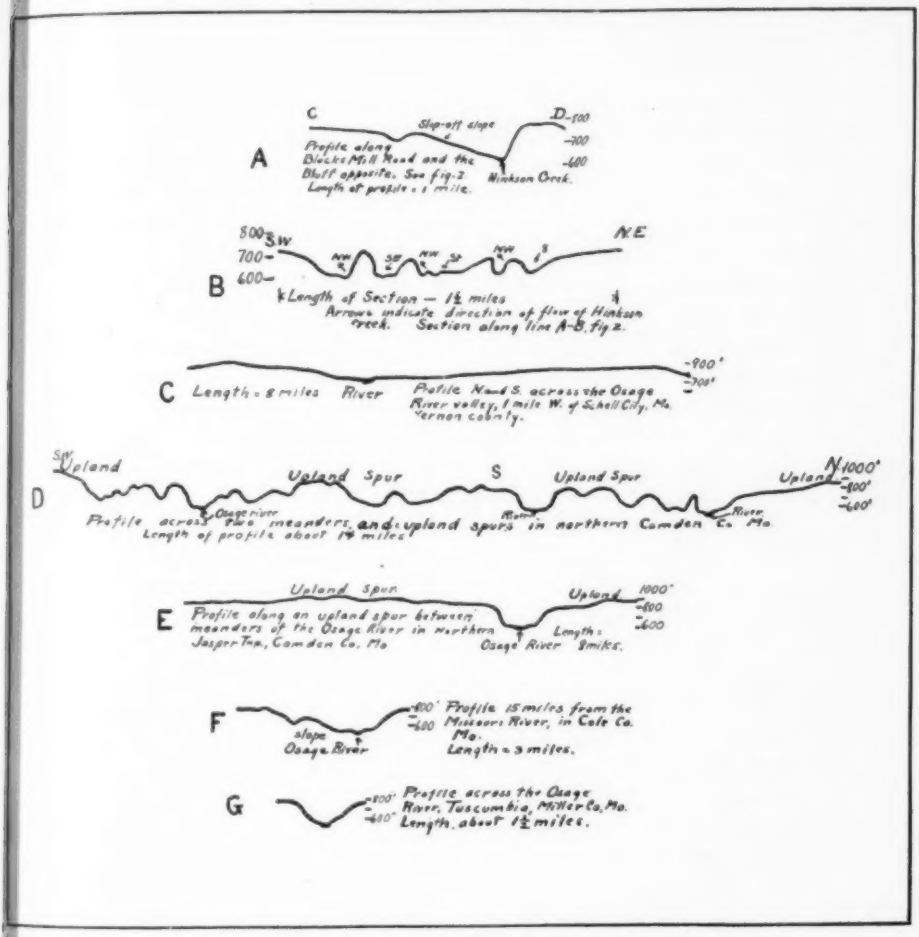
A
Profile along Blacks Mill Road and the Bluff opposite. See fig. 2
Length of profile = 1 mile.
Slip-off slope
Hinkson Creek.
B
Length of Section — 1½ miles
Arrows indicate direction of flow of Hinkson Creek. Section along line A-B, fig. 2.
C
Length = 8 miles
River
Profile N and S. across the Osage River valley, 1 mile W. of Shell City, Mo. Vernon county.
D
Upland
Upland Spur
Upland Spur
Upland
Osage river
River
Profile across two meanders and upland spurs in northern Camden Co. Mo.
Length of profile about 14 miles.
E
Upland Spur
Upland
Profile along an upland spur between meanders of the Osage River in northern Jasper Twp., Camden Co. Mo
Length = Osage River 3 miles.
F
slope
Osage River
Profile 15 miles from the Missouri River, in Cole Co. Mo.
Length = 3 miles.
G
Profile across the Osage River, Tuscumbia, Miller Co. Mo.
Length about 1½ miles.

FIG. 6.—Profiles of the Hinkson Creek (*A* and *B*) and of the Osage River (*C*, *D*, *E*, *F*, and *G*).

illustrates the type of meandering stream suggested by Winslow,[1] and assumed by him as the probable method by which the Osage, Gasconade, and other streams of the Ozark Plateau developed their present courses. This, however, is not the origin of the intrenched meanders of these streams as will be shown below.

MEANDERS OF THE OSAGE RIVER AND ITS TRIBUTARIES

The Osage River is the largest southern tributary of the Missouri River in Missouri. Rising in east central Kansas, it follows an easterly course to central Missouri, then northeast to join the Missouri River a short distance east of Jefferson City.[2] The length of its course in Missouri is 331 miles. This study includes also 52 miles in Kansas, beginning at Osawatomie, Kansas, giving a total length of 383 miles. The river flows across Pennsylvanian rocks, mainly shales, with some sandstone and limestone, to the northeast corner of Vernon County, Missouri (Fig. 1), and from there to the Missouri it flows entirely on limestone and dolomite with occasional beds of sandstone and shale.

Throughout the entire distance of 383 miles, the stream has a meandering course. There is a marked difference in the character of the meanders between the upper and lower portions, however. From Osawatomie, Kansas, to the border line of the Ozark Plateau (Fig. 1) the river meanders widely on a broad flat flood plain (profile *c*, Fig. 6). From this point in western St. Clair County, the valley narrows rapidly until, within a few miles, the valley walls are close to the river and only a narrow flood plain, usually developed on one side of the river, exists. The river still retains its meandering course, the meanders becoming larger and larger and the bluffs on each side increasing in height until they attain a maximum of nearly 300 feet in the vicinity of Linn Creek, Camden County, at which point the Osage is the farthest up on the Ozark Plateau. From here to the Missouri River the bluffs gradually decrease until they are about 150 to 175 feet high. The accompanying

[1] *Op. cit.*

[2] See the following topographic sheets of the U.S. Geological Survey: Mound City and Olathe, Kansas; Butler, Clinton, Warsaw, Versailles, Tuscumbia, and Jefferson City, Missouri.

sketch (Fig. 7) drawn on the same scale, shows the comparative size of the meanders of the upper portion (near Rich Hill, Bates County, Missouri) and the lower portion (St. Thomas, Cole County, Missouri) (Fig. 1, *A* and *B*). The two sections of the river are about 270 miles apart.

The Osage is a typically intrenched stream from Osceola (near the center of St. Clair County) to its mouth. The valley walls are

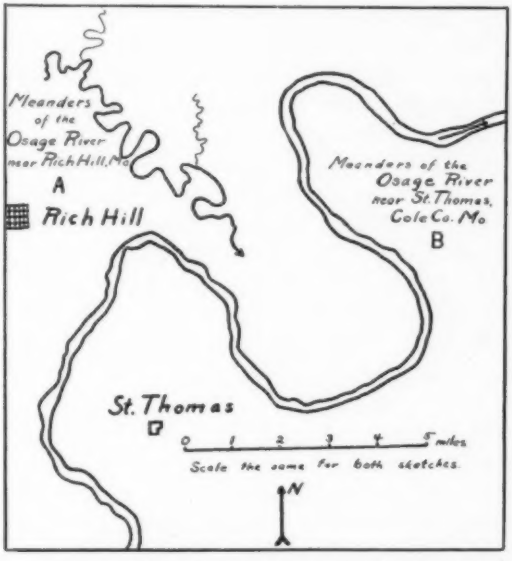
Meanders of the Osage River near Rich Hill, Mo.
A
Rich Hill
Meanders of the Osage River near St. Thomas, Cole Co. Mo
B
St. Thomas
0 1 2 3 4 5 miles
Scale the same for both sketches.
N

FIG. 7.—Comparison of the meanders of the upper (near Rich Hill, Missouri) and lower (near St. Thomas, Missouri) courses of the Osage River.

steep on both sides and closely parallel the river. There are minor variations from uniform steepness on both sides, but a careful study of the river throughout its course shows that on the average the two sides are uniformly the same. Nearer the Missouri River this uniformity is lost because the river here is nearer grade. Its gradient is 6.96 inches per mile in this part of its course, and it is cutting laterally, thus steepening one side while erosion is rounding up the opposite slope.

The meanders near Linn Creek in Camden County, where the river is the farthest up on the Ozark Plateau, are striking evidence of intrenchment. The meanders are several miles in length, and inclose overlapping upland spurs which are continuous with the surrounding upland (elevation, 900 feet above sea-level). These spurs have an elevation of 850 and 900 feet. Both valley walls are steep at the sides and ends of the spurs (profiles *D* and *E*, Fig. 6). Profile *D* crosses the Osage River three times and shows very well the uniformity in the valley walls on each side. Profile *E* is taken along the crest of the upland spur in the large meander in Jasper Township in north Camden County. The noticeable feature here, and that which proves that the Osage is an intrenched stream, is the increase in elevation of the upland spur to nearly 900 feet at its end and the sharp and rapid plunge to the river bottom and rapid rise to the mean elevation on the opposite side of the river. If the Osage had intrenched itself by lateral cutting as well as downward it would have developed a slip-off slope along this spur such as the Hinkson has developed (Figs. 2–5 and profile *A*, Fig. 6). Profile *E* shows that the Osage has been cutting downward only and has thus intrenched itself below the upland. A glance at the contour maps and profiles of the Hinkson and the Osage shows at once that they represent two different methods of intrenchment.

If the Osage River did not develop slip-off slopes at the point where it has intrenched its valley the deepest, and where it had to do a maximum amount of cutting, then it certainly did not do so where its valley is shallower. In short, if the river had developed its present meanders from smaller original irregularities in its course by lateral migration accompanied with downward cutting, profiles such as those in *D* and *E* would have been impossible.

Profile *G*, Figure 6, is at Tuscumbia, Missouri, a point some 35–40 miles below Linn Creek. It should be noted that in this older portion of the stream, where the grade is less, the valley is U-shaped and that in profile *F*, Figure 6, within 15 miles of the Missouri River, the upland spur (right) has considerable slope toward the river. No doubt the damming of the waters in the Osage, and probable aggrading of its valley, had something to do with this shape. How high the water stood in this valley is not known, save

that glacial bowlders have been found 75 feet above the present level of the Osage.

The tributaries of the Osage tell the same story as the parent-stream. The Grand River meanders widely on a flat flood plain in its upper course in west central Missouri, but, as soon as it reaches the uplifted area, its meanders are strongly intrenched (see Warsaw sheet). Cole Camp Creek (same sheet) shows a similar series of intrenched meanders that are splendidly developed. There is no flood plain, the valley walls are 150–200 feet high and cling closely to every curve of the stream. The Niangua River (Versailles sheet), flowing into the Osage from the south, shows some fine intrenched meanders. Big Gravois Creek (same sheet), entering from the north, shows intrenched meanders, and shows also how rejuvenation, working up the creek from the Osage, has reached the headwaters of the stream. Another excellent example is Big Tavern Creek on the Tuscumbia sheet.

The lower course of the Osage and its tributaries tells but one story, that of a drainage system which found itself superimposed on an area that was rising. It responded actively and as the area arose it intrenched itself, until today some portions of its channel are nearly 300 feet below the upland.

MEANDERS OF THE GASCONADE RIVER

The Gasconade is the second largest tributary of the Missouri on the south. It rises in the west central part of the Ozark Plateau near the southern part of Wright County and flows northward down the slope of the Ozark Plateau and enters the Missouri about 30 miles below the Osage River. Although its meanders are not so large as those of the Osage, they are fully developed for the size of the stream. Its principal tributaries, Roubidoux, Big Piney, and Little Piney creeks, flow into it from the east and south and have similar meandering courses. Only a small portion of the Gasconade has been mapped topographically; hence the conclusive evidence that has been shown along the Osage cannot be given for this stream. The writer has seen the river in several places, and in all the evidence of intrenchment is plainly seen.

THE MERAMEC AND ITS TRIBUTARIES

The Meramec River rises at the crest of the watershed of the Ozark Plateau in Dent County, and flowing first north, then northeast, east, and southeast, enters the Mississippi River 20 miles south of St. Louis. It has a large tributary on the north, the Bourbeuse River, and one from the south, Big River. Both parent-stream and tributaries are noted for their meandering courses. A study of the topographic sheets which show these streams reveals abundant evidence of their being intrenched meanders. Figure 8 is a sketch of a portion of the Bourbeuse River on the Sullivan, Missouri, Quadrangle and shows the extreme meandering of this stream. The Meramec and its tributaries have been at grade longer than either the Osage or Gasconade, and, as a result, their meanders show more downstream migration, with consequent widening of their flood plains. The upland spurs closely entwined by the meanders leave no doubt that these streams owe their intrenchment to the same agent as that acting on the Osage and Gasconade.

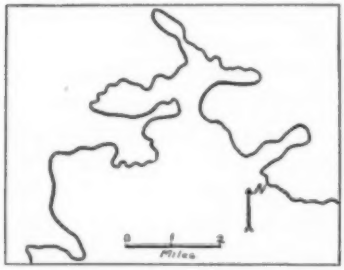

FIG. 8.—Meanders of the Bourbeuse River, a tributary of the Meramec River, near Union, Missouri.

CAUSE OF INTRENCHMENT

The intrenchment of the streams of the northern slope of the Ozark Plateau, the Osage, Gasconade, and Meramec, was caused by an uplift that followed peneplanation. The incisement of Hinkson Creek to the north of the plateau was due to static rejuvenation, rather than uplift.

The Ozark Plateau was certainly peneplained during the Tertiary and possibly also during the latter part of the Mesozoic. The Ozark area was reduced to a plain above the general level of which rose only a few unreduced remnants of the original land surface. This peneplain truncates the various geologic formations of

the Ozark area. The Missouri River was in existence during this time and received the drainage of the northern slope of the plateau as it does today. In late Tertiary times, probably late Pliocene in fact, although some authors think it may have been Middle Tertiary, the Ozark area was uplifted. This (late Pliocene) was a period of uplift over much of the United States and a movement of several hundred feet is believed to have occurred in the Mississippi Valley. The maximum movement involved the southern half of Missouri and the northern part of Arkansas, the axis following approximately the dotted line in Figure 1.

The Osage, Gasconade, and Meramec rivers flowed across this peneplain in meandering courses with wide valleys. As the area came up, these streams and the Missouri were rejuvenated and began cutting downward. The meanders they possessed at the time of uplift were preserved because the rate of uplift was about equal to the ability of the streams to cut downward. At present they have largely ceased to cut downward and are engaged in widening their flood plains by cutting into their valley walls. The lower courses already have flood plains a half to three-quarters of a mile wide. This conclusion as to the intrenchment of the Osage and other streams is in accord with that of Davis,[1] rather than that of Winslow.

The Osage shows how a stream may hold its own against uplift in its lower course, if the rate of upward movement does not exceed the cutting power of the stream. The upper course of the Osage, topographically, is old and the lower course, exclusive of the meanders, which are younger topographically, is in early maturity. Such an anomaly in streams indicates rejuvenation.

The Gasconade and Meramec lie entirely upon the Ozark Plateau; hence they show rejuvenation throughout their entire courses.

The Hinkson, lying as it does on the northward margin of the uplifted area and uninfluenced by the uplift, began incising its valley after the Kansan ice sheet had retreated from this area, and developed its incised meanders by static rejuvenation as the channel of the Missouri River, into which it empties, was lowered.

[1] *Science*, Vol. XXI (1893), pp. 225–27; Vol. XXII (1893), pp. 276–79.

SUMMARY

The meanders of Hinkson Creek and of the Osage, Gasconade, and Meramec rivers have been described in detail in order to bring out the fact that the Hinkson began its incisement much later than the rivers to the south began to intrench themselves, and has developed its meanders through lateral and downward cutting, thus producing "incised meanders" with "slip-off slopes" on the upland spurs. This type of meander has been called an "incised meander" to distinguish it from the simple downward cutting of the intrenched rivers to the south. The incised meanders of the Hinkson are due to static rejuvenation (caused by the downward cutting of the parent-stream, the Missouri River), and the intrenchment of the Osage, Gasconade, and Meramec rivers is due to the uplift of the entire area across which the three streams had previously developed meandering courses on wide flood plains. This uplift is believed to have occurred in late Pliocene times. Since that time the Tertiary peneplain has been undergoing dissection, thus producing the restful and beautiful mature topography for which the Missouri Ozarks are justly famous.

THE OSBURN FAULT, IDAHO[1]

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Oklahoma City, Oklahoma

ABSTRACT

The Osburn fault crosses northern Idaho and presents conclusive evidence of a horizontal component of movement measurable in miles. The plane dips about 65° from the horizontal and, incident to movement along it, sympathetic fractures hundreds of feet long have been opened and reopened as shown by the sequence of mineral deposition in the Cœur d'Alene district. The reverse faults of the area have much less gouge than the normal ones, indicating that they were caused by vertical rather than horizontal stresses. These stresses may have arisen from an underlying molten intrusion—a possibility supported by the ore deposits which are genetically related to the granite and by lamprophyre dikes along the fault plane, some of which are crushed by later movements. As the mineralization accompanied both the granite intrusion and the faulting, it is suggested that movement along the Osburn fault involved gliding on a molten subsurface zone.

The magnitude of the Osburn fault and its position in the hanging wall of the Lewis and Philipsburg overthrusts normal to their strike suggests that they may be related phenomena. As there is some suggestion that the two thrusts were not synchronous, it is possible that the Osburn plane separates great blocks which at different times moved eastward.

DESCRIPTION OF THE FAULT

The Osburn fault, long recognized as an earth fracture of major importance, is the most pronounced tectonic feature of northern Idaho. It crosses the state in a west-northwesterly direction, passing through Shoshone County in the vicinity of Wallace. The fault can be easily recognized as far west as the mouth of Fourth of July Canyon, and it continues eastward beyond the Continental Divide. The geology of opposite sides of the fault plane has been studied in detail for a distance of about 30 miles, both on the surface and in numerous mine workings. Throughout this distance, it approximately coincides with the old valley described by Calkins and Jones as extending from Spokane, Washington, to Deer Lodge, Montana, a distance of about 300 miles.[2] As this valley crosses the prevailing structural axes of the region, it seems

[1] Published with the permission of the Director of the U.S. Geological Survey.

[2] F. C. Calkins and E. L. Jones, Jr., "Economic Geology of the Region around Mullan, Idaho, and Saltese, Montana," *U.S. Geol. Survey Bull. 540* (1913), pp. 169, 176.

probable that the faulting which determines its course in Idaho also determines its course in Montana.

> At Mullan the fault disappears beneath the alluvial floor of the valley, which is so broad for some distance eastward as to baffle any effort to trace the fault directly, and the upper part of the valley, which is narrower, has not been fully examined for evidence of its continuation to the east. The old valley, however, is clearly located on a fault or fault zone whose identity with the Osburn fault, though perhaps it cannot be absolutely proved, is strongly indicated by its direction and position and the fact that, like the Osburn fault, it effects in most places a downthrow on the south.[1]

The fault has been crossed in numerous mine workings and prospects, which afford an excellent opportunity to study it in detail. In general there is a central mass of gouge a few feet wide, with numerous parallel gouge seams both in the hanging wall and in the footwall. Thus the fault must be considered a complex fracture with many planes of movement distributed through a zone locally 100 or 200 feet wide. The main fault plane in every exposure examined dips between 60° and 70° south. Locally igneous material, principally lamprophyre, follows the fault zone, indicating that it existed as a zone of weakness during the period of magmatic activity in the region. In places, such igneous material is crushed by later movement along the fault.

The apparent vertical displacement caused by the Osburn fault is widely different in different places, ranging from less than 1,000 feet to more than 10,000 feet, but, even after allowing for such vertical displacements, it is impossible to fit the opposite sides together into anything like a regular arrangement. Anticlines are opposite synclines; major north-south faults are cut off abruptly; and cross-folds that might explain the great differences in apparent displacement are lacking. These difficulties suggest a pronounced horizontal component of movement and led Hershey[2] to make a detailed study of the problem. He found that a peculiar purple phase of the Burke formation abundant in the vicinity of Kellogg south of the fault was absent from the Burke formation directly

[1] F. C. Calkins, and E. L. Jones, Jr., "Economic Geology of the Region around Mullan, Idaho, and Saltese, Montana," *U.S. Geol. Survey Bull. 540* (1913), pp. 169, 176.

[2] O. H. Hershey, *Origin and Distribution of Ore in the Cœur d'Alene* (private publication), Min. and Sci. Press, 1916.

north of the fault, but that 12–15 miles farther east, in the vicinity of the town of Burke, this same purple banding characterizes the formation.[1] The purple coloring in each locality increases in intensity eastward. Hershey also correlates several minor structural features north and south of the fault, each indicating a movement of the south side from 10 to 16 miles westward relative to the north wall. Even more convincing than these evidences, however, are certain broad features brought out by work of the writer and E. L. Jones, Jr., in the Pine Creek district, which lies south of the fault and west of Wardner. Here the rocks have a domelike structure, with the Burke and Revett formations flanking the Prichard on the east. The continuation of this structure north of the fault appears between Osburn and Ninemile Creek. Also the lead-silver deposits at Wardner lie east of the Pine Creek zinc-producing belt, and north of the fault the Canyon Creek lead-silver deposits are about the same distance east of the zinc deposits on Ninemile Creek. A large fault in the Pine Creek area, known as the Government Gulch fault, may be correlated with some assurance with the Carpenter Gulch fault which dips in the same direction and also forms the contact between Burke and Prichard rocks. Some of the offset structural features dip east and some of them dip west, yet all of them indicate westward shift of the south side relative to the north side. This new evidence indicates a horizontal component of movement of about 12 miles, which accords with Hershey's conclusion that the horizontal component "may have been 10 or 15 miles."

RELATED PHENOMENA

This great fault, comparable in many respects to the San Andreas Rift of California, presents problems of origin and relation to other geologic phenomena which are of particular interest. Before proceeding with the discussion of them, however, it will be necessary to review briefly the major structural features of the general Idaho-Montana region and particularly certain detailed relationships of structure, ore deposition, and magma invasion in the Cœur d'Alene mining district.

[1] For geologic and geographic detail refer to *U.S. Geol. Survey Bull. 732* (1922), Plates I and II.

The structural features of northern Idaho and western Montana involve moderate folding and extensive faulting (Fig. 1). Over much of the area the great series of Algonkian sediments known as the Belt Series is steeply tilted, and although individual axes of folding cannot be traced for great distances numerous faults have been followed for many miles and found to have displacements of several thousands of feet. Calkins states: "The great faults of

FIG. 1.—Index map

the region are mostly steep and probably the majority of them are normal, although a normal character has not been actually proved in many cases. The downthrow of all the steeply inclined faults, except the great Lenia fault and the one west of Bull River, is to the west and south."[1]

Along the east side of this area is the great Lewis overthrust described by Willis,[2] and the Philipsburg overthrust described by

[1] F. C. Calkins, "A Geological Reconnaissance in Northern Idaho and Northwestern Montana," *U.S. Geol. Survey Bull. 384* (1909), p. 52.

[2] Bailey Willis, "Stratigraphy and Structure of the Lewis and Livingston Ranges, Montana," *Bull. Geol. Soc. America*, Vol. XIII (1902), pp. 305–52.

Calkins,[1] each of which presents an overthrust from the west measurable in miles.

As the region for nearly 200 miles west of the Lewis and Philipsburg overthrusts constitutes a physiographic, petrographic, and metallogenetic province, it seems reasonable to accept as a working hypothesis a genetic relationship between the major structural features of the region, and to suspect that the mineral deposits,

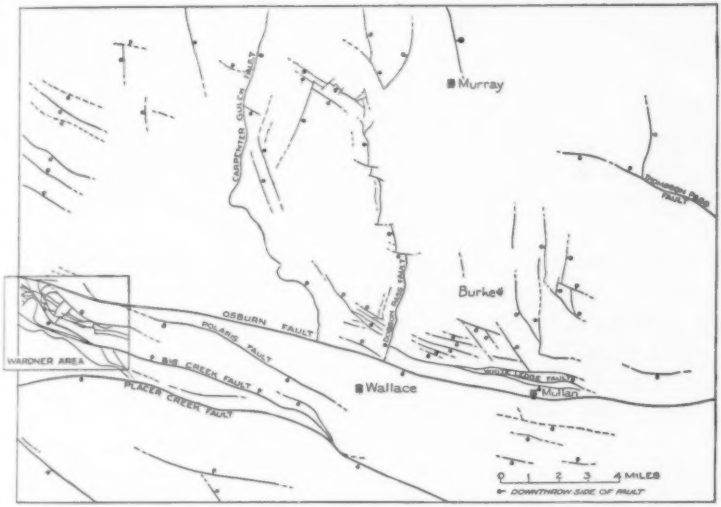

FIG. 2.—Faults of the Cœur d'Alene district, Idaho. (Principally after F. C. Calkins.)

great igneous masses, and structural features are genetically related to each other.

The Cœur d'Alene district (Fig. 2) lies toward the western edge of this province. Its surface is a greatly dissected plateau, standing at an elevation of approximately 6,000 feet and tilted gently northward. Its country rocks are mainly sediments of Algonkian age which consist of many thousand feet of fine-grained quartzites of varying purity, shales, and impure limestones. Locally these

[1] F. C. Calkins and W. H. Emmons, "Geology and Ore Deposits of the Philipsburg Quadrangle, Montana," *U.S. Geol. Survey Professional Paper 78* (1913), pp. 146–50.

strata are invaded by masses of monzonite and syenite, accompanied by a number of lamprophyre dikes. These are almost certainly outliers of the great Idaho batholith, which crops out over a continuous area of more than 20,000 square miles in the central part of the state.

The subdivision of the sedimentary rocks is more or less a matter of convenience because few sharp transitions occur in the sequence. For the same reason the recognition of faults of less than a few hundreds of feet displacement is impossible in most places.

The ore deposits of the Cœur d'Alene, with the possible exception of the gold quartz veins near Murray, present all transitions between such widely diverse types as the disseminated copper of the Snowstorm mine, the chalcopyrite-siderite lodes of the southern copper area, the Success deposit with contact metamorphic characteristics, the zinc lode of the Interstate-Callahan mine, and the Bunker Hill and Sullivan galena-siderite deposits. Even the antimony lodes are linked to the others by many essential features in common. The chief minerals were formed in a fairly definite sequence, readily recognized in most of the lodes. Siderite was deposited first, followed by quartz, sphalerite, and galena in the order named. In some of the lodes siderite is nearly absent and in others galena is negligible, suggesting an opening of some fissures and a closing of others during the period of mineral deposition. That structural disturbances accompanied mineral deposition is also shown by the prevailing occurrence of galena and other late minerals as seams in the older minerals and by the relations in the Wardner area, where there are three systems of lodes with different strike and dip, all of which contain the same essential minerals, deposited in the same order but in different relative amounts. In *Bulletin 732* of the U.S. Geological Survey, the writer and E. L. Jones, Jr., discuss the problems of ore genesis in considerable detail. For the present it may be sufficient to say that the observed differences of the ore deposits of the area seem to be due to a recurrent opening of fractures in different directions at different times during a period in which an underlying magma was giving off solutions of gradually changing composition.

The structural features of the Cœur d'Alene district may be grouped broadly in order of age as folding along northeast-southwest axes, faulting along north-south axes, and later faulting and folding along west-northwest axes. The faults of the third group, which includes the Osburn fault, are in part older than the ore deposits, in part younger, and in part the same age. Normal and reverse faults occurred in both the second and third periods of diastrophic activity. The normal faults in general have dips between 50°

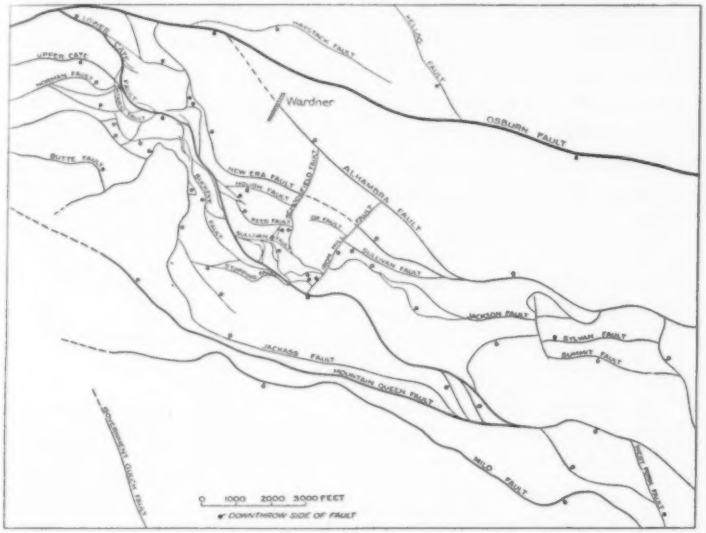

FIG. 3.—Traces of faults, Wardner area, Idaho. (Principally after O. H. Hershey.)

and 80°, but the Dobson Pass fault, with a minimum displacement of 8,000 feet, has a dip of only 30°. Concerning the reverse faults Calkins states:

> A part only, as the Ucelly Gulch and Carpenter Gulch faults, have the low dips generally considered characteristic of overthrusts; but a far greater number, clearly seen in mine workings, have dips of 50° to 80° and although having displacements amounting to thousands of feet are accompanied by so little crushing and disturbance that it is impossible to conceive of their having been formed by lateral pressure alone.[1]

[1] F. L. Ransome, and F. C. Calkins, "The Geology and Ore Deposits of the Cœur d'Alene District, Idaho," *U.S. Geol. Survey Professional Paper 62* (1908), p. 62.

Hershey[1] recognizes this fact in the Wardner area (Fig. 3) and observes that "the normal faulting made stronger gouges than reverse faulting." This observation, made by both Calkins and Hershey and fully borne out by the writer's fieldwork, is most important, because it indicates that vertical rather than horizontal stresses operated in developing the reverse faults. These faults were formed by a lifting force which lessened the pressure of the hanging wall against the footwall instead of increasing it, as would a horizontal thrust of sufficient force to cause an upward gliding of the hanging wall of a steep fracture. This force may reasonably be credited to the underlying batholith, which is believed to be the source of the ore-forming solutions.

The west-northwest folding is conspicuous only in the vicinity of the Osburn fault and south of it. Two anticlines cross Big Creek Valley, and an overturned fold parallels the Osburn fault from Big Creek to Wallace. This is overturned northward, inplying a thrust from the south. South and east from Wallace a broad syncline, with similar strike, crosses the north fork of St. Joe River and Slate Creek.

EFFECTS OF CURVATURE OF THE FAULT PLANE

In view of the great horizontal component of movement on the Osburn fault, curvature of the fault plane suggests problems of particular interest. If the points where the fault leaves the east and west boundaries of the area represented on the map of the Cœur d'Alene district[2] are used to determine a straight line, it appears, after corrections for the dip of the fault plane and differences in elevation of the surface, that the fault curves gradually southward, reaching a point 4,200 feet south of its general course in the vicinity of Wallace. Thus as movement of the hanging wall progressed relatively westward, there was near Wallace a protuberant part of the footwall offering particular resistance to the movement. It is a striking fact that the east-west folding

[1] O. H. Hershey, "Genesis of the Lead-Silver Ores in Wardner District, Idaho," *Min. and Sci. Press*, Vol. CIV (1912), p. 30.

[2] J. B. Umpleby and E. L. Jones, Jr., "Geology and Ore Deposits of Shoshone County, Idaho," *U.S. Geol. Survey Bull. 732* (1923), Plate II.

previously described is limited to the hanging wall opposite to, and for a few miles west of, this proturberance, and the question arises how far the disturbed zone which in general parallels the fault may have developed incident to the 12 miles or so of movement along its curved plane. The walls must have been in places crowded forward into major re-entrants and elsewhere crowded back by great protuberant segments. Certainly there is no evidence that a gaping fissure ever existed.

The net tendency of the stresses would be to slice the protruding segment parallel to the general course of the Osburn fault. Thus may be explained the localization and intensity of the east-west faulting in the area near Mullan. But what of the hanging-wall segment opposite this bulge in the footwall? As it moved westward it had a tendency to occupy positions successively farther from the footwall (Fig. 4). But lateral pressure was sufficient to keep the fault

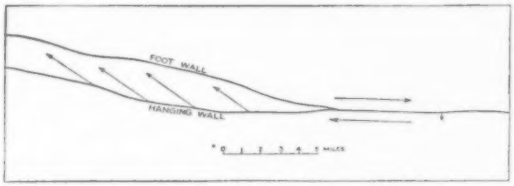

FIG. 4.—Diagram illustrating the effect of horizontal displacement along the curved plane of the Osburn fault.

fissure closed and hence there must have been a crowding forward of this part of the hanging wall to keep in contact with a footwall that curved northward away from it. Furthermore, as the net result along the Osburn fault was a relative shifting of the south side westward there must have been a strong component of force in that direction. This, however, was probably the major component of a stress that operated obliquely to the direction of movement because the fissure remained closed. Thus it is probable that as the shifting progressed planes of fracture oblique to the main one would develop, breaking the rocks into slices, and that each slice would advance more than the one northeast of it. In this way the intense slicing of the Wardner area and the progressive shifting

of the south slices westward along lines oblique to the Osburn fault may be accounted for, as illustrated by Figure 3.

The peculiar localization of particularly intense faulting in the Wardner area south of the fault and in the Mullan area north of the fault, whereas simple structure is found across the fault from both these areas, is a striking feature of the region and baffling to explain, except as a direct result of the horizontal movement along the curved plane of this great displacement in the earth's crust (Fig. 2).

DURATION OF PERIOD OF FAULTING

The Osburn fault has not been found to be cut by any other faults and is believed to be an uninterrupted earth fracture. There is evidence, however, of recurrent movements along it. Where cut off by the Osburn fault in the Senator Stewart mine, the plane of the New Era fault is bent from a westward dip, and its strike turns sharply to the northeast, showing drag phenomena on a tremendous scale and indicating a relative westward shifting south of the Osburn fault. The Wardner area comprises a great number of thin slices which stand on edge and converge with the Osburn fault toward the west. If these structural features are incident to movement along the major fault it would seem that they should show shifting of each slice toward the northwest relative to its neighbor on the northeast. That such shifting has resulted is well shown in the Bunker Hill and Sullivan Mine where the Jersey fissures, two parallel veins with northeast strike, are cut off by the Upper and Lower Cate faults and the south segments set some 800 feet to the west.

Mineralization persisted throughout much of the general period of faulting, but ore deposition principally accompanied the faults of reverse displacements. These also were recurrent and have been shown to have less gouge than the faults of normal type, a fact believed to be due to readjustments in an underlying magma. Thus it appears that ore deposition, which is younger than the granite and older than its lamprophyre derivatives, accompanied stages of particular activity within a magma underlying the region and connects this activity with movements along the Osburn fault.

In the Burke area and in the vicinity of Mullan, stresses causing a nearly vertical slicing of the rocks were operative. In many of the lodes here it is impossible to distinguish sharply between fissuring and shearing. Cleavage parallel to the ore bodies occurs throughout the long cross-cuts leading to the Morning and Gold Hunter deposits, and schistosity parallel to the lode is conspicuously developed in the Hecla mine. In the region about Murray a similar phenomenon may be recognized, though here it is much less pronounced. It may be observed as a generalization that the farther removed the deposits are from the Osburn fault, the less pronounced is shearing and the more prevalent is simple fissuring.

The movements that caused the shearing were evidently recurrent, as shown by the recurrent sequence of mineral deposition along later fractures that offset older ones.

AGE OF THE FAULT

The Osburn fault cuts all the rock formations of the area in which it has been studied in detail. Westward it passes beneath the Miocene basalt of the Spokane area. But as the age of the Cœur d'Alene stratified rocks is Algonkian, this fixes only very wide limits.

The limits may perhaps be narrowed by consideration of the intrusive rocks. It has been shown above that at least much of the movement along the fault accompanied mineralization in the Cœur d'Alene district at a time when an underlying magma was giving off lamprophyre dikes and that some of these dikes, crushed by later movement, follow the fault plane. The age of the granitic rocks of the Cœur d'Alene region cannot be determined from local evidence, but it seems quite reasonable to assume that they represent the same general period of intrusive activity as does the great central batholith of Idaho. The rocks of both regions are similar, bear the same general relation to mineral deposits, extend upward to the level of an Eocene erosion surface, and are connected by a chain of similar intrusives. The great Idaho batholith has been assigned, on fairly safe evidence, to the late Cretaceous or possibly to the early Eocene, and the similar rocks of the Cœur d'Alene region are believed to be of about the same age.[1]

[1] J. B. Umpleby, "Geology and Ore Deposits of Lemhi County, Idaho," *U.S. Geol. Survey Bull. 528* (1913), pp. 42–43.

It seems most reasonable, therefore, to assign the Osburn fault to the late Cretaceous or early Eocene.

RELATION TO THE LEWIS AND PHILIPSBURG OVERTHRUSTS

The relationship of the Osburn fault to the great overthrusts to the east is of particular interest as their magnitude and the many common characteristics of northern Idaho and western Montana suggest that they may be related phenomena. The geographic relations are shown in Figure 1. From a study of the literature it appears that the Philipsburg overthrust is older than the Lewis overthrust. Calkins found that the youngest rocks involved in the overthrust fault at Philipsburg were shales of Colorado age and that the granite rocks of early Tertiary age cut the fault plane. On the other hand, Willis assigned the Lewis overthrust to the mid-Tertiary. More recent work, however, by Campbell and his associates places this fault as post-Cretaceous and pre-Miocene. The reasons for this determination as stated briefly by Mr. Campbell are as follows:

> The rocks in actual contact with the Belt Series and over which it was thrust are at least middle Cretaceous and all of the Cretaceous that is known in this region is involved in the folds that were probably produced contemporaneously with the faulting. It is barely possible that some rocks of Tertiary age are involved also in these folds, but that, I believe, has not been clearly established. The reason for regarding the fault as pre-Miocene is that in the valley of North Fork of Flathead River on the west side of the Park, rocks of Miocene age are cut by normal faults which, according to my interpretation, could not have been done prior to the great overthrust as this thrust must have been transmitted thru them from the west. I am therefore assuming that the overthrust occurred first and then that the overthrust mass was subject to tension and the normal faults were produced.[1]

Work by other geologists of the Federal Survey places the Lewis fault in the late Eocene or early Oligocene.[2]

From available data, therefore, it appears that the Philipsburg and Lewis overthrusts, although occurring along the same general axis, were not synchronous movements and that the Lewis fault is the younger.

[1] M. R. Campbell, personal communication dated March 28, 1924.

[2] G. R. Mansfield, "Structure of the Rocky Mountains in Idaho and Montana," *Bull. Geol. Soc. America*, Vol. XXXIV (1923), p. 269.

As the relative offset is to the east on the north side of the Osburn fault, the commonly accepted view that the Philipsburg and Lewis overthrusts implies a movement from the west toward the east suggests that the north side of the Osburn fault was the active element. Perhaps opposed to this, however, are the facts that the plane of the Osburn fault dips south and the hanging wall is the down-throw side, although its strike appears to favor the interpretation. Alternative hypotheses might assume that (1) the Osburn fault resulted from tension set up behind the Philipsburg overthrust after it had developed, (2) the Philipsburg and Lewis faults are underthrusts from the east rather than overthrusts from the west, (3) the Osburn fault has no close genetic connection to either of the faults to the east, or (4) there was an early movement east on the south side of the Osburn fault synchronous with the Philipsburg thrust and a later movement east on the north side at the time of the Lewis thrust. It was hoped that this problem could be solved by reproducing the fault pattern in the laboratory under controlled conditions of pressure and resistance but, although the pattern has been closely approximated, this particular question remains unanswered. Its solution is believed to involve much more field data than are now available.

CONCLUSIONS

In summary, the Osburn fault, probably of late Cretaceous or early Eocene age, is a steeply dipping earth fracture of unusual length, the hanging wall of which has shifted some 12 miles westward relative to the footwall. Its displacement represents the sum of a number of movements, a part of which at least were contemporaneous with mineral deposition in the area. As the mineralization accompanied the solidification of an outlier of the great Idaho batholith, it follows that at least some of the displacement took place during the magma stage. This is also suggested by the meager gouge on the related faults of reverse character and the occasional presence of lamprophyre dikes along the Osburn fault, some of which are crushed and shattered. As detailed studies indicate that the mineralization accompanied the granitic

intrusion on the one hand and the faulting on the other, it is suggested that the great movement along the Osburn fault involved gliding on a molten subsurface zone.

The position of the Osburn fault in the hanging-wall side and at right angles to the Philipsburg and Lewis overthrusts, the belief that the development of these faults was not synchronous, the unusual magnitude of the three faults, and the fact that each developed in the late Cretaceous or early Tertiary suggest a genetic relation the nature of which remains undetermined.

THE CHEMISTRY OF THE EARTH'S CORE

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ABSTRACT

In this contribution I have endeavored to determine the constituents of the earth's core as well as the percentages of such constituents. The proof depends upon the premise that chemical laws are universal as regards both time and space. By such an assumption we are able to confirm many known facts, such as the earth's siliceous crust, and also to solve many problems when given a sufficient number of known facts. The known facts are the mass and density of the earth, the composition and density of the outer 10 miles of crust, and the specific gravity of the various elements. Although two variations of the problem are briefly considered it will probably be found that the results obtained in the main proof more nearly approach the truth, and indicate a composition of approximately 90 per cent of iron; 7 per cent of nickel, cobalt, and copper; and 3 per cent of the remaining elements.

Since the interior of our earth has a volume of nearly 260,000,000,000 cubic miles, it is but natural that we should feel sufficient interest in its study to make gladly every effort to broaden our knowledge of its general character.

Much progress has already been made, and the following are a few of the facts that are now generally accepted as true: (1) the earth's density as a whole is approximately 5.55; (2) the density of the outer crust is approximately 2.75; (3) the earth as a whole is extremely rigid; (4) at great depths the pressure is prodigious; (5) the internal temperature, in parts at least, is at a white heat; (6) the chemical composition of the outer 10 miles of crust is quite accurately known (see Table I).

As much of the recent investigation has been in connection with the earth's origin, its internal heat, rigidity, vulcanism, ore bodies, and the chemistry of igneous rocks and of the lithosphere, I shall not dwell upon these matters except in so far as they relate to the subject of the chemical composition of the earth's core.

This is a subject that has been passed by in most cases as entirely too speculative for serious thought, but it is far from certain that it

cannot be worked out satisfactorily. The writer made an attempt to do so many years ago, employing rather similar reasoning as at present, but lack of necessary information at that time made the subject difficult of proof. Since then considerable advance has been made in the study of geology, and I am now more hopeful that a proof is possible. While I do not entertain the slightest idea that this article will be found sufficiently convincing to win acceptance, it might at least furnish some thought or suggestion that may enable someone better fitted than myself to solve the problem.

In what follows I shall apply the term "lithosphere" to designate the oxidized portion of the earth—including, of course, the silicate, carbonate, sulphate, phosphate, and other oxidized rocks, as well as other petrogenic matter, and the term "core" to designate what is supposed to be a concentration toward the center of heavy metallic elements.

Glancing over the known facts, we note that the earth's density as a whole is 5.55, while that of the lithosphere is 2.75. It is evident that the density of the interior must be greater than 5.55, due in all probability to the presence of heavy material of some kind at some lower horizon. Our problem, therefore, is to determine which elements are present and in what amounts.

But the facts just stated are insufficient for determining these questions, for an unlimited number of combinations are possible. A thick lithosphere inclosing a comparatively small core of a heavy metal could give the same earth density (5.55) as a shallow lithosphere inclosing a large core of a light metal. For instance, the density of the earth would remain unchanged whether we had a core of gold composing 17 per cent of its volume, or a core of antimony composing 72 per cent of its volume.

This at once suggests the idea that if we could determine the thickness of the lithosphere, we could then calculate the size and density of the core, and our problem would be solved. Undoubtedly such information would be extremely valuable, but unfortunately it would still be insufficient, for the core might consist of a complex alloy. For instance, suppose that its density were seven. This is the density of zinc, and we would be inclined to believe that the earth's interior consists of a mass of zinc; and yet there might be

little or no zinc present, the density being due to a combination of two or more metals in the proper proportion to give such a density, as, for instance, iron and aluminum, aluminum and copper, magnesium and silver, sodium and lead, manganese, nickel, calcium, and lithium, and so on without end.

It is therefore evident that further information is necessary, and referring to the known facts mentioned at the beginning of this article, we observe that the composition of the outer portion of the lithosphere is quite accurately known. In my opinion this information, if properly applied, offers a possible means of reasoning out this subject, when taken in conjunction with the fixed densities referred to above.

Starting with fundamentals, we know that if certain chemical elements are brought together under proper conditions, certain reactions will take place. These elements might be brought together in a distant nebula or star, in the sun or earth's crust, in a Bessemer converter or a laboratory crucible, but regardless of where they may be brought together, so long as the conditions are favorable, similar results will be produced, for the law of chemical affinity is just as universal as the law of gravitation.

And so if we have sodium, silicon, and oxygen present under favorable conditions, the sodium and silicon will be oxidized to sodium oxide and silica, and these will then combine and form sodium silicate.

Let us now assume the presence of iron. Iron, having less affinity for oxygen than either the sodium or silicon, will oxidize less rapidly, and will be but partially oxidized when the sodium and silicon are almost entirely oxidized. The fact is that both the sodium and silicon, while being oxidized, will furnish protection to the iron against oxidation, but while this protection is considerable, it is not perfect.

Carrying this a step farther, assume the presence of a larger number of elements such as sodium, magnesium, manganese, iron, nickel, copper, silver, and gold. If oxygen (or air) be passed through a fusion of these metals, oxidation will proceed in the order of their relative oxidizabilities (which is in the foregoing order), each metal in turn, while undergoing oxidation, serving to protect those that

follow, guarding them to a considerable extent against oxidation, until it be itself completely oxidized.

But if the supply of oxygen should become exhausted before all of these had been oxidized, for instance during the oxidation of the iron, then all the metals more oxidizable than the iron (providing that sufficient silica and flux are present to satisfy the oxides formed) would be found largely in the slag, while those less oxidizable than the iron would be present in but comparatively small amounts in the slag.

It is therefore possible to obtain a fair idea of the nature of a metallic fusion as well as the degree of its oxidation by studying the resulting slag. If the slag should show little iron, it would not necessarily prove that little iron had been present, for the low percentage might indicate that oxidation had not advanced far, but if considerable iron were in the slag, we might not know just what percentage of the iron had been oxidized, but we could be certain that the greater part of all elements more oxidizable than the iron would be in the slag, and this would include in every case the potassium, sodium, lithium, barium, strontium, calcium, magnesium, aluminum, as well as the rarer elements in the same corresponding periodic groups, as, for instance, radium.

In the case of elements which are less oxidizable than iron, as copper, nickel, etc., similar reasoning can be applied as has been applied to the iron, that is, that their oxidation would be retarded until the greater part of the iron had been oxidized, and then each in turn would be oxidized according to its relative oxidizability. But during the period that this oxidation was retarded, the retardation would not be complete, and all the metals would simultaneously undergo some oxidation, according to their amounts and their oxidizabilities.

This brings up the subject of chemical losses, and too much emphasis cannot be laid on the practical impossibility of obtaining chemically pure substances by any simple method, it being necessary as a rule to employ laborious methods with frequent retreatments. And so if any element be present to any extent, it is almost certain to make its presence known through entering the slag, and the percentage of this loss in most cases is very material, particularly when

no attempt is made to separate the individual substances by special methods.

Chemical affinity is the chief determining factor in chemical reactions. While oxygen is the active agent in most of these reactions, it is not essential; but as it is so predominant over all other so-called acid elements as chlorine, fluorine, sulphur, arsenic, antimony etc., they can safely be ignored in this discussion, and all reactions that have the effect of forming slag or rock substances will be considered as oxidations.

Summing up the various facts presented, we have: (1) A marked discrepancy in specific gravity between that of the combined slag and metal and that of the slag would indicate the presence of considerable heavy unoxidized metals. (2) The chemical composition of the slag offers valuable information of the nature of these heavy unoxidized metals. (3) The various elements in a fusion will successively undergo oxidization in the order of their relative oxidizabilities. (4) Each element while undergoing oxidation will protect against oxidation all other elements of less oxidizability than itself. (5) If oxidation ceases before all of the elements are oxidized, as, for instance, during the oxidation of the iron, then part of the iron and the greater part of the more oxidizable elements will be found in the slag, and part of the iron and the greater part of the less oxidizable elements will be found unoxidized. (6) A large amount in the slag of a comparatively difficultly oxidizable element as iron would indicate the almost complete oxidation of all the more oxidizable elements and their presence in the slag. (7) The amounts in the slag of the less oxidizable elements are proportional to their oxidizabilities and to their relative amounts originally present. (8) Chemical losses are practically impossible to avoid, due to the great difficulty of obtaining perfect separations by any process.

From the foregoing facts it is evident that it is extremely important to learn if possible in partial oxidations which element was undergoing oxidation when the supply of oxygen was exhausted, for with this knowledge we are able to determine which elements are mainly in the slag, the elements that largely remain unoxidized, and also the measure of oxidation of the element partially oxidized.

Now applying this information to the earth itself, we know that its volume is approximately 260,000,000,000 cubic miles, and that its density is about 5.55.

In order to simplify the calculation, I shall assume for the present that the earth is a perfect sphere, and that the metallic contents of its interior are concentrated in a spherical core surrounded by a shell of siliceous rock, uniform in composition, and extending to the surface.

These statements will be modified later.

If we represent the weight of 1,000,000 cubic miles of water by one K-ton, then the weight of a volume of water equal to that of the earth will be 260,000 K-tons, and the weight of the earth will be 5.55 times this amount, or 1,443,000 K-tons.

The volume of the lithosphere is equal to the volume of the earth less the volume of the core, and its weight could then be figured from its density of 2.75; or if we knew the thickness of the lithosphere, the same results could be obtained. But unfortunately we do not know either the volume of the core or the thickness of the lithosphere, so an indirect method must be employed, based on the chemical theory previously stated.

The first step necessary is the calculation of the volume of the lithosphere or the core, for without this information we are unable to apportion the respective densities to the core and lithosphere.

In what follows, as I intend to substitute the word "lithosphere" for "slag," and "core" for "metallic fusion," a brief explanation is necessary.

Regardless of whether we assume the nebular hypothesis or the planetesimal hypothesis to be true, the elements that compose the earth were at one time dissociated. The various elements, however, when conditions became favorable, combined and reacted, undergoing oxidations and reductions, decompositions, separations, recompositions, and various other chemical changes, but at all times tending toward more stable forms. The result of chief importance was the serial oxidation of the various elements so long as free oxygen existed, and the combination of the basic oxides with silica, forming the siliceous lithosphere, which is the most stable form under which such elements will combine, as proved by the testimony of meteorites, terrestrial rocks, and furnace slags.

Such chemical changes are universal if conditions are favorable, but the question arises, Have the conditions been favorable? We have admitted that pressure in the earth's interior is prodigious, and such conditions might cause entirely different chemical actions to occur than would take place under normal pressure. This is true, but, nevertheless, I believe that this very point strengthens the proof, because such proof is largely built up around chemical combinations and chemical losses, and the former are assisted by pressure, and the latter increased by pressure, due to reduced fluidity of the molten rocks or magmas under great pressure; and I therefore believe that the comparison of the lithosphere to slag is not only proper but is entirely on the side of safety.

So making this substitution to statement 6 on page 619, we have the following: A large amount in the lithosphere of a comparatively difficultly oxidizable element as iron would indicate the almost complete oxidation of all the more oxidizable elements and their presence in the lithosphere.

But if it be true, in the case of the earth, that oxidation ceased before the oxidation was complete, then we are particularly interested in knowing which element was undergoing oxidation at that time, because we should then know which elements are principally in the lithosphere.

It should not be difficult to show that iron is the metal that is partially oxidized. As the ratio between the densities of the earth and the lithosphere is as 2 to 1, we know that there must be a concentration of heavy matter of some kind in the interior. We note that the percentage of iron in the lithosphere is far higher than that of most of the easily oxidizable elements, proving thereby that the iron must have undergone considerable oxidation. But we also note that there is a great discrepancy between the amount of iron and the amount of all other elements that are less oxidizable than itself. With a percentage of iron in the lithosphere of 5.12 per cent, if the iron were entirely oxidized we would have one of two results: first, the density of the earth could not be far from 2.75; and second, the percentage in the lithosphere of one or more of the less oxidizable elements should be far higher than is the case, because after the iron were oxidized, these elements would then be rapidly oxidized, and a high percentage shown in the lithosphere. But as

the density of the earth is 5.55 and not 2.75 and as the highest percentage of any of the low oxidizable elements is only 0.019 per cent, we know that iron must be present in great amount, and that it is but partially oxidized. Therefore, iron must have been the metal that was principally undergoing oxidation at the time that oxidation ceased, and consequently all elements more oxidizable than the iron must necessarily be found largely in the lithosphere.

This enables us to eliminate from the present discussion those elements more oxidizable than iron. The list includes the following

TABLE I

1. Oxygen	46.43	23. Lithium	0.003
2. Silicon	27.77	24. Copper	0.002
3. Aluminum	8.14	25. Cerium, etc	0.001
4. Iron	5.12	26. Glucinum	0.00xx
5. Calcium	3.63	27. Cobalt	0.00xx
6. Sodium	2.85	28. Boron	0.000x
7. Potassium	2.60	29. Zinc	0.000x
8. Magnesium	2.09	30. Lead	0.00000xx
9. Titanium	0.629	31. Arsenic	0.00000xx
10. Phosphorus	0.130	32. Cadmium	0.0000xx
11. Hydrogen	0.127	33. Tin	0.0000xx
12. Manganese	0.096	34. Mercury	0.0000xx
13. Fluorine	0.077	35. Antimony	0.0000xx
14. Chlorine	0.055	36. Molybdenum	0.0000xx
15. Sulphur	0.052	37. Silver	0.000000xx
16. Barium	0.048	38. Tungsten	0.000000xx
17. Chromium	0.037	39. Bismuth	0.000000xx
18. Zirconium	0.028	40. Selenium	0.00000000xx
19. Carbon	0.027	41. Gold	0.00000000xx
20. Vanadium	0.021	42. Bromine	0.00000000xx
21. Nickel	0.019	43. Telurium	0.000000000xx
22. Strontium	0.018	44. Platinum	0.000000000xx

elements: silicon, aluminum, calcium, sodium, potassium, magnesium, titanium, phosphorus, hydrogen, fluorine, chlorine, sulphur, barium, zirconium, carbon, vanadium, strontium, lithium, caesium, glucinum, boron, bromine, as well as many of the rarer elements including radium, to which reference was made. It is also evident that the oxygen has been almost entirely eliminated.

Later on, all of these elements will be considered as possible constituents of the core, but now we are principally concerned with determining the volumes of the lithosphere and core, and therefore aim to determine the most important constituents of the latter.

The preceding table (Table I) gives the percentages of the various elements in the outer 10 miles of lithosphere, according to Henry S. Washington.[1]

The "xx" represent digits and are indeterminate between 1 and 9, although their decimal positions are supposed to be correct. For our purpose they are sufficiently accurate, however, with the possible exception of cobalt, which I trust will be determined more accurately before long.

Eliminating from the list those elements which have been shown to be principally found in the lithosphere, and which consequently cannot possibly be of prime importance as constituents of the core, we have the following list:

TABLE II

Iron	5.12	Mercury	0.0000xx
Manganese	0.096	Antimony	0.0000xx
Chromium	0.037	Molybdenum	0.0000xx
Nickel	0.019	Silver	0.000000xx
Copper	0.002	Tungsten	0.000000xx
Cobalt	0.00xx	Bismuth	0.000000xx
Zinc	0.000x	Selenium	0.0000000xx
Lead	0.000xx	Gold	0.0000000xx
Arsenic	0.000xx	Telurium	0.00000000xx
Cadmium	0.0000xx	Platinum	0.00000000xx
Tin	0.0000xx		

In the determination of the thickness or volume of the lithosphere, all of the more oxidizable elements having been eliminated, it will now be shown that the greater number of the less oxidizable elements can also be eliminated.

In this proof each of these elements will be considered as if it made up the entire core, and use will be made of what was emphasized earlier as "chemical losses." If these losses are too absurdly low, it will be evident that the element to which that loss applies cannot be considered of importance in this connection. Confirmation of this will be shown later in Table V. I shall endeavor to make this clearer.

In the case of the lighter, easily oxidizable elements, we naturally expect to find them in the lithosphere, and their absence from there

[1] "Chemistry of the Earth's Crust," reprinted from the *Journal of the Franklin Institute*, 1920.

is exceptional. But in the case of the elements beginning with iron (Table II), their natural location is the core and not the lithosphere, and with the exception of iron and a few others, their presence in the lithosphere is exceptional, and can be considered in the nature of a loss as in any metallurgical process. Iron is found naturally in both the core and the lithosphere because it is but partially oxidized, and the percentage found in the lithosphere is the measure of its degree of oxidation. By examining Table II, it is seen that iron is more than fifty times more abundant in the lithosphere than the next metal in order (manganese), and it would therefore seem apparent that iron preponderates over all these elements. But small percentages in the lithosphere do not mean much to us, as our experience has never considered them in this manner. We might say, How do we know that 0.000xx per cent of lead is too insignificant to consider? The fact is we do not know, as we have never viewed the subject in this way. But if we could estimate the results in terms of loss ratios, we would then be on more familiar ground, for we know that losses under the most favorable conditions are very material, and if we should find that under less favorable conditions they are many hundred times less than they should be, we would then know that the amount necessary to produce such a minute loss must be small and consequently unimportant in the present discussion.

If we should determine the total amount of any metal present in the entire earth and figure the ratio between this amount and the amount in the lithosphere, we should then have the loss ratio.

It will now be shown that no element but iron can possibly make up the entire core of the earth and give a proper loss ratio. For instance, I shall assume that the earth has a core of iron. The volume of the core plus the volume of the lithosphere must equal the volume of the earth, or 260,000,000,000 cubic miles, while the weight of the core plus the weight of the lithosphere must equal the weight of the earth, or 1,443,000 K-tons. The density of iron (7.86) must be applied to the volume of the core to obtain its weight, while the density of the lithosphere (2.75) must be applied to the volume of the lithosphere to obtain its weight. Each metal in turn will be assumed to make up such a hypothetical core, the

weights of the core in each case being determined from the proper specific gravity for that metal, while the weights of the lithosphere in every case are figured from a density of 2.75. As shown earlier in the article, the lithosphere becomes larger and the core smaller for the heavier metals as silver, gold, platinum etc., and vice versa for the lighter metals as arsenic, antimony, chromium, etc. By referring to Table III we find in every case that the sum of the volumes of the core and lithosphere for each metal equals approximately 260,000,000,000 cubic miles and the weight of the core and lithosphere approximately 1,443,000 K-tons. There is a slight variation on account of failure to carry out the calculations to a sufficient number of decimal places.

Now, following the calculation through for iron, we note that its specific gravity is 7.86. With such a specific gravity, and for the lithosphere of 2.75, we find that the volume of the core is 142,500,000,000 cubic miles, and the volume of the lithosphere is 117,500,000,000 cubic miles. We find that the weight of the core is 1,120,050 K-tons, and the weight of the lithosphere is 323,125 K-tons.

As the lithosphere weighs 323,125 K-tons, and the percentage of iron in the lithosphere is 5.12 per cent, we find that the amount of iron in the lithosphere amounts to 16,544 K-tons. The sum of the weight of the core plus the iron in the lithosphere should give the weight of iron in the entire earth. The ratio between this figure and that of the iron in the lithosphere gives the loss ratio, or, in other words, the amount of oxidation that the iron has suffered. We find it to be 1.455 per cent, which is entirely reasonable.

Treating the various metals in the same way, we find that manganese shows a loss of .023 per cent which is less than one-sixtieth part of that of the iron, and since manganese is more oxidizable than iron, the discrepancy will consequently be even greater. In the same way chromium shows a loss ratio of one two-hundred-and-fortieth that of iron, and it likewise is more oxidizable than iron, which makes the difference still greater. Nickel shows a loss ratio of one two-hundredth that of iron, but this is a better showing because nickel is less oxidizable than iron; and the same can be said of the copper and the cobalt. Zinc and lead show poorer

TABLE III

Element	Specific Gravity	Volume of Core in Terms of 1,000,000 Cubic Miles	Volume of Lithosphere in Terms of 1,000,000 Cubic Miles	Weight of Core in K-Tons	Weight of Lithosphere in K-Tons	Percentage in Lithosphere	Weight of Element in Lithosphere in K-Tons	Total Weight in Core and Lithosphere in K-Tons	Percentage of Loss
Iron	7.86	142,500	117,500	1,120,050	323,125	5.12	16,544.000000	1,136,594	1.455
Manganese	7.39	157,000	103,000	1,160,230	283,250	.096	271.920000	1,160,502	.023
Nickel	8.8	120,300	139,700	1,058,640	384,175	.019	72.993250	1,058,713	.007
Chromium	6.7	184,300	75,700	1,234,810	208,175	.037	77.024750	1,234,887	.006
Copper	8.93	117,800	142,200	1,051,954	391,050	.002	7.821000	1,051,962	.0008
Cobalt	8.6	124,400	135,600	1,069,840	372,900	.005	18.645000	1,069,859	.002
Zinc	7.0	171,300	88,700	1,199,100	243,925	.0005	1.219625	1,199,101	.0001
Lead	11.34	84,700	175,300	960,498	482,075	.0005	2.410375	960,500	.0003
Arsenic	5.72	245,100	14,900	1,401,972	40,975	.0005	.204875	1,401,972	.00002
Cadmium	8.64	123,600	136,400	1,067,904	375,100	.00005	.187550	1,067,904	.00002
Tin	7.28	160,700	99,300	1,169,896	273,075	.00005	.136539	1,169,896	.00001
Mercury	13.55	67,400	192,600	913,270	529,650	.00005	.264825	913,270	.00003
Antimony	6.62	188,100	71,900	1,245,222	197,725	.00005	.098863	1,245,222	.000008
Silver	10.47	94,300	165,700	987,321	455,675	.000005	.022784	987,321	.000002
Molybdenum	9.0	116,500	143,500	1,048,500	394,625	.00005	.197313	1,048,500	.000002
Tungsten	19.1	44,300	215,700	850,560	593,175	.000005	.029658	850,560	.000003
Bismuth	9.8	103,200	156,800	1,011,360	431,200	.000005	.021560	1,011,360	.000002
Gold	19.2	44,300	215,700	850,560	593,175	.0000005	.002966	850,560	.0000004
Platinum	21.4	39,000	221,000	834,600	607,750	.00000005	.000304	834,600	.00000004
Telurium	6.25	208,000	52,000	1,300,000	143,000	.00000005	.000072	1,300,000	.000000006

results, the zinc showing a loss of about one fifteen-thousandth of the iron, and lead about one five-thousandth.

The best result after zinc is mercury, which shows a ratio between itself and iron of about 1 in 50,000.

It must be evident to anyone that such a loss ratio is inconceivably low, and that therefore such metals could not possibly make up more than a very small part of the core.

Iron has a specific gravity of 7.86, while the manganese, nickel, chromium, copper, cobalt, zinc, and lead, taken collectively, give a specific gravity not very different from that of iron, but as iron is in large excess over the combined weight of these metals, no appreciable error can possibly be made by assuming a specific gravity for the interior of 7.86.

Consequently, we can use the same figures for volume and weight of core and lithosphere as we did for iron, and thus have a weight for the core of 1,120,050 K-tons, and for the lithosphere of 323,125 K-tons.

This then becomes our starting-point for Tables IV and V. Table IV is a preliminary table to Table V, and consists merely in determining the weight of each element in the lithosphere, using the percentages shown in Table I, and applying these to the foregoing weight.

We thus find, for instance, that the weight of the silicon in the lithosphere is 89,731.8125 K-tons; that of aluminum is 26,302.3750; of iron, 16,544; manganese, 310.2; nickel, 61.3938; copper, 6.4625; silver, .0162, platinum, .0002 K-tons.

We now come to the most interesting table (Table V), in which the subject is treated quantitatively, an attempt being made to determine the percentages of the various elements present in the core. Once more the relative oxidizabilities of the various elements are called into play.

We have shown that if the earth has a core of iron, oxidation would have proceeded to that point at which the iron would have suffered oxidation to the extent of 1.455 per cent.

We also referred to elements as being more or less oxidizable than iron. But for our purpose these terms are too general, and it will be necessary to subdivide them further. For instance, sodium,

potassium, calcium, magnesium, aluminum, etc., are grouped as easily oxidizable elements, and yet they vary among themselves; for calcium, magnesium, and aluminum are less oxidizable than sodium and potassium. While we would naturally expect almost

TABLE IV

Element	Weight of Litho-sphere in K-Tons	Percentage in Lithosphere	Weight of Element in Lithosphere in K-Tons	Element	Weight of Litho-sphere in K-Tons	Percentage in Lithosphere	Weight of Element in Lithosphere in K-Tons
O.....	323,125	46.43	150,026.9375	Li.....	323,125	.003	9.6938
Si.....	323,125	27.77	89,731.8125	Gl.....	323,125	.005	16.1563
Al.....	323,125	8.14	26,302.3750	Co.....	323,125	.005	16.1563
Fe.....	323,125	5.12	16,544.0000	Cu.....	323,125	.002	6.4625
Ca.....	323,125	3.63	11,729.4375	Zn.....	323,125	.0005	1.6156
Na.....	323,125	2.85	9,209.0625	Pb.....	323,125	.0005	1.6156
K.....	323,125	2.60	8,401.2500	As.....	323,125	.0005	1.6156
Mg.....	323,125	2.09	6,753.3125	B.....	323,125	.0005	1.6156
Ti.....	323,125	.629	2,032.4563	Ce.....	323,125	.001	3.2313
P.....	323,125	.130	420.0625	Sb.....	323,125	.00005	.1616
H.....	323,125	.127	410.3688	Cd.....	323,125	.00005	.1616
Mn.....	323,125	.096	310.2000	Sn.....	323,125	.00005	.1616
Ni.....	323,125	.019	61.3038	Hg.....	323,125	.00005	.1616
Cr.....	323,125	.037	119.5563	Mo.....	323,125	.00005	.1616
F.....	323,125	.077	248.8063	Ag.....	323,125	.000005	.0162
Cl.....	323,125	.055	177.7188	W.....	323,125	.000005	.0162
S.....	323,125	.052	168.0250	Bi.....	323,125	.000005	.0162
Ba.....	323,125	.048	155.1000	Au.....	323,125	.0000005	.0016
Zr.....	323,125	.028	90.4750	Se.....	323,125	.0000005	.0016
C.....	323,125	.027	87.2438	Br.....	323,125	.0000005	.0016
Va.....	323,125	.021	67.8563	Pt.....	323,125	.00000005	.0002
Sr.....	323,125	.018	58.1625	Te.....	323,125	.00000005	.0002

TABLE V

Elements	Factors	K-Tons in Lithosphere	K-Tons in Core and Lithosphere	Percentage of Total Weight	K-Tons in Core	Percentage of Core
O, H, C, K, Na, Li.....	95.00	168,144.5564	176,994.27	12.26	8,850	.790
Ba, Ca, Sr, Si, B.....	90.00	101,676.1281	112,973.47	7.83	11,297	1.009
Mg, Al, Ce, Gl.....	80.00	33,075.0751	41,343.84	2.86	8,269	.738
Va, Zr, Ti, F, Cl, Br.....	50.00	2,617.3143	5,234.63	.36	2,617	.234
Cr, S.....	25.00	287.5813	1,150.32	.08	803	.077
Zn, Cd, Mo, W, P.....	10.00	422.0175	4,220.18	.31	3,798	.339
Mn.....	10.00	310.2000	3,102.00	.22	2,792	.249
Fe.....	1.455 1.62	.....	.....	.....	.....	.....
Sn, Hg, Se, Te Bi, Pb, As, Sb.....	0.50	3.7340	746.80	.05	743	.066
Co.....	0.25	16.1563	6,462.52	.45	6,446	.576
Ni.....	0.10	61.3938	61,393.80	4.25	61,332	5.477
Cu.....	0.08	6.4625	8,078.12	.56	8,072	.721
Ag.....	0.03	0.0162	54.00	.....	54	.005
Au, Pt.....	0.005	0.0018	36.00	.....	36	.003

complete oxidation of all of these elements at the time that the iron had undergone oxidation to the extent of 1.455 per cent, the oxidation might not have been absolutely complete, and there would be greater likelihood of calcium, magnesium, and aluminum remaining partly unoxidized than the sodium and potassium.

However, the attempt to arrange them in this way is beset with difficulties, because so many varying conditions can influence the results, as, for instance, temperature variations and various chemical combinations. Take the case of phosphorus. We know that this element is very oxidizable, and yet when combined with iron as a phosphide of iron, it is oxidized with considerable difficulty, and, consequently, a comparatively low figure is assumed for it.

On account of the difficulty of arranging each element in its exact position in relation to the other elements, the case is greatly simplified by grouping most of the elements. This is no disadvantage because the results in most cases are very small, while it has a distinct advantage in averaging results.

I have assumed, therefore, that when 1.455 per cent of iron had been oxidized that 95 per cent of the hydrogen, carbon, potassium, sodium, and lithium had also been oxidized, and 90 per cent of the calcium, barium, strontium, silicon, and boron; and 80 per cent of the magnesium, aluminum, cerium, and glucinum. Lower percentages are assumed for vanadium, zirconium, titanium, fluorine, chlorine, bromine, chromium, sulphur, zinc, cadmium, molybdenum, tungsten, and phosphorus. Manganese is not grouped with the zinc, cadmium, etc., as I wished to show that even though manganese is more abundant in the lithosphere than either nickel or copper, it is relatively of less importance.

Of the elements that are less oxidizable than iron, I have also assumed values representing as before the percentages of these elements that would have been oxidized when 1.455 per cent of the iron had been oxidized.

Figures are given for gold and platinum, although in all probability no oxidation occurred, but without doubt these metals suffered some mechanical loss, particularly if the earth had been built up according to the planetesimal hypothesis formulated by Professor T. C. Chamberlin. This is probably the true explanation of the earth's origin, and I shall assume it to be true in explaining certain details later on.

Referring now to Table V, we find the symbols of the various elements in the first column, and in the second column are given the oxidation ratios just explained, but which can also be regarded as the ratios existing between the amounts in the lithosphere and the total

amounts in the earth. Of course, it is not strictly true that oxidation would entirely explain the transference of an element from the core to the lithosphere, but this subject was previously considered, and attention called to the fact that as oxidation played such an overwhelming part in this transference we would consider it as the entire cause, as any error through so doing would be practically negligible.

Thus, the total amount of any element in the earth multiplied by its respective oxidation factor gives the amount of that element in the lithosphere, and, vice versa, dividing the amount of any element in the lithosphere by its respective oxidation factor determines the total amount in the earth of that element. The difference between this amount and the amount in the lithosphere gives the amount in the core which is the amount sought.

No difficulty should be experienced in following this table except for a change in the iron factor from 1.455 to 1.62. The reason for this is that the core was figured as if it were composed entirely of iron. The core is, however, made up of other elements besides iron, so the iron content had to be reduced that amount which made the ratio of total iron to iron in the lithosphere 1.62 instead of 1.455. Theoretically the figures should have been changed for all of the other elements, but for the more oxidizable ones, very slight changes would result whether 1.455 or 1.62 of iron had been oxidized, while the percentages of the less oxidizable ones are so small that the results would not have been materially changed by making such an allowance.

Now the interesting parts of the results in this table are the following: (1) The core consists of about 90 per cent of iron, followed by nickel, copper, and cobalt. (2) The total percentage in the core of oxygen, hydrogen, carbon, potassium, sodium, lithium, barium, calcium, strontium, silicon, boron, magnesium, aluminum, cerium, glucinum, vanadium, zirconium, titanium, fluorine, chlorine, bromine, chromium, sulphur, zinc, cadmium, molybdenum, tungsten, and phosphorus amounts to but about 3 per cent. (3) While the nickel and cobalt agree quite closely with analyses of meteorites, the results for copper show a marked discrepancy, the ratio of copper to nickel being over 10 per cent instead of less than 1 per cent

in the case of meteorites. But if the nickel is correct, the copper must of necessity be fairly correct, providing no error has been made in the percentage of copper in the lithosphere. It is quite possible, however, that the planetesimals that formed the earth were much richer in copper than are the meteorites that now fall to the earth.

In this article I have been compelled to depend largely on theory, but I believe that it should not prove such a difficult matter to demonstrate these facts within certain limits. I consider it quite unlikely that any material error has been made in the results for iron, or for the easily oxidizable elements, or for those found in very small amounts in the lithosphere, but I do feel some uncertainty regarding the results for nickel, cobalt, and copper. The following simple test might possibly throw some light on the results: Make a mixture of about 71 pounds of iron, $4\frac{1}{4}$ pounds of nickel, $\frac{1}{2}$ pound of copper, $\frac{1}{2}$ pound of cobalt, 15 pounds of quartz, $4\frac{1}{2}$ pounds of alumina, $2\frac{1}{4}$ pounds of lime, and $1\frac{1}{2}$ pounds of soda, and *slowly* oxidize the mixture by the Bessemer process. When an analysis of the slag shows an iron content of about $1\frac{1}{2}$ per cent, discontinue the oxidation and determine the percentages of the nickel, cobalt, and copper. In case there is much variation from the results in Table V, a new table should be constructed, substituting these figures for the oxidation factors employed in that table.

When Professor Chamberlin first published his "Planetesimal Hypothesis," he attributed the earth's high density to pressure; but in his later works he has apparently abandoned that idea. As it is possible, however, that pressure might have had some effect in increasing the earth's density, I shall construct a new table (Table VI), making allowance for a partial increase of density from that cause.

In this table I shall assume, because of increased pressure, that the lithosphere has an average density of 4, and the iron content of the core has an average density of 10. While the method of calculation is quite similar to that shown in Table V, the chief difference in results is an increase in the volume and weight of the lithosphere, and a corresponding reduction in the volume and weight of the core. With these new ratios we find that iron would have suffered oxidation to the extent of 5.55 per cent instead of 1.455 per cent, as in

Table V. But if the oxidation of iron were three or four times as great, then all of the other elements should show an increase in oxidation, except perhaps those that were almost completely oxidized in the first place. We find when assuming these conditions that the weight of the lithosphere becomes 771,332 K-tons, and the

TABLE VI

Elements	Percentage of Lithosphere, 771,332	K-Tons in Lithosphere	Oxidization Factor Per Cent	K-Tons in Core and Lithosphere	K-Tons in Core	Percentage in Core
O, H, Na, C, K Li, Si, Ca, B, Ba Sr, Mg, Al, Ce, Gl	93.740	723,046.617	95	761,101	38,054	5.66
Va, Zr, Ti, F Cl, Br, Cr, S	.899	6,934.275	60	11,557	4,623	.69
Zn, Cd, Mo W, P, Mn	.227	1,750.924	40	4,377	2,626	.39
Fe	5.12	39,492.198	6.37 5.55	619,942	580,450	86.44
Sn, Hg, Bi, Pb As, Sb	.001	7,713	2	386	378	.06
Co	.005	38,567	1	3,857	3,818	.57
Ni	.019	146,553	.4	36,638	36,491	5.43
Cu	.002	15,427	.3	5,142	5,127	.76

weight of the core 671,668 K-tons. Calculating, as previously explained, and comparing the results for iron, nickel, cobalt, and copper with those in Table V, we have the following comparisons:

TABLE VII

Element	Table V	Table VI
Iron	89.716	86.44
Nickel	5.477	5.43
Cobalt	0.576	0.57
Copper	0.721	0.76

It is thus seen that the differences are not very great and that the proof does not materially suffer through the assumption of a slight increase in density due to pressure. Of course, if the pressure in itself could explain the high density of the earth, then there could be no core.

Another possibility is an increase in basicity at lower horizons. This possibility would be entitled to more consideration if the earth

had during its formation passed through a state of fusion, but this theory is being rapidly rejected for the planetesimal theory of Professor Chamberlin. But assuming it to be true, the result would be a smaller core, but at the same time richer in iron, and probably also in nickel, cobalt, and copper.

Thus, in every case we find that iron is predominant, followed by nickel, cobalt, and copper. We also find that the other elements are present in but small amounts in the core, although the more oxidizable ones make up the greater part of the lithosphere.

Earlier in this article, for the purpose of simplifying the calculations, I assumed a clear demarcation between the core and lithosphere. The fact of the matter is that while there is undoubtedly a concentration of heavy elements toward the center of the earth and of lighter ones toward the surface, any clean separation is extremely unlikely. But as silicates and unoxidized metals do not combine, even though they are intimately mixed they may be considered as entirely separate, regardless of whether there be a clearly defined core or a more or less intimate mixture of these materials. But I do not believe that the materials as a whole are intimately mixed, and I herewith refer to various passages in Professor Chamberlin's book, *The Origin of the Earth*, which should clear up not only this question, but also those relating to pressure and those relating to underlying basic rocks.

From the beginning the earth is pictured as growing up largely by the accession of solid planetesimal dust.

> They remained solid except as specific conditions enforcing liquefaction arose after their burial and reduced selected portions to the molten state. . . . . The adjustment tracts were probably mechanically selected in each stratum or group of strata while still near the surface. . . . . The chief mode by which solid rocks under high pressure and heat adjust themselves to great stress differences is by recombinations and recrystallizations. . . . . A portion of the energy that had been engaged in maintaining the volume of the mass was turned by compression into heat, and this powerful agency for both chemical and physical change was brought into action. . . . . Stress conditions are held to be a vital agency in forcing liquid matter to the surface as fast as formed in workable quantities, except as the specific gravity may have been high enough to resist this. . . . . Without doubt . . . . the tidal and rotational stress differences . . . . were greatest at the center and graduated outwards . . . . while pressing equally in all directions at any given point, yet

they had a selective effect which of itself tended to force the lighter liquids to the surface. . . . . There seems to be good warrant in observed vulcanism . . . . for the generalization that molten rock is, and probably always has been persistently squeezed out of the earth by the stresses and strains that permeate it. On the other hand the residue should have increased in average refractoriness by the selective action and by the recombinations that had been induced in the interest of stability. . . . . The selective process by the removal of the silicates in larger proportions than the metals and metallic alloys probably tended to concentrate the latter towards the center and to make them ultimately a large part of the residuum. . . . . The inner reorganization of the juvenile earth is, therefore, pictured as a process that affected persuasively the whole interior of the earth, preserving effectively the solid state of the main mass, and progressively increasing its average rigidity, while at the same time it set free and forced towards the surface, stage by stage, the lighter and more mobile matter. . . . . The process was long for the growth was gradual; much of the material came to the surface, again underwent burial, reheating and reorganization; again came to the surface and so on. . . . . The mutations of the inner earth may be summarized as a single prolonged process, by which the more fluent, solvent and lighter material of the earth-body was concentrated towards the surface, while the more immobile refractory and heavier matter was concentrated towards the center. The result may be pictured as a central core dominated by metallic alloys, and a thick enveloping sphere dominated by silicates. . . . . It is probable that the concentration of the metallic elements towards the center contributed to increasing complexity in the alloys of the earth's core.

These views of Professor Chamberlin uphold the theory of a probable metallic core and silicate shell, and while there is but little likelihood of these being very uniform in structure, they are nevertheless so distinct in composition that they should be considered as absolutely distinct in every way. In the same manner we can safely conclude that the high density of the earth is due to heavy metallic alloys and not to increased density of rock material through pressure. The explanation of the gradual growth of the earth through alternate burials and extrusions should indicate quite conclusively a fairly uniform composition for the lithosphere. It is therefore most unlikely that acidic rocks should be found underlaid by basalts or other basic rocks; and, consequently, the assumption of a lithosphere of average specific gravity of 2.75 per cent is probably not far from the truth.

Summing up the subject, we can picture the earth as consisting of an irregular core of metallic substances surrounded by an irregular

shell of silicate rock. The former makes up about 77.5 per cent of the earth's weight, and the latter about 22.5 per cent. The metallic portion is probably more or less mixed with rock material, while the silicate shell is more or less mixed with metallic substances. The silicate shell has approximately the composition given in Table I and corresponds to a diorite, while the core probably consists of about 90 per cent of iron; 7 per cent of nickel, cobalt, and copper; and about 3 per cent of the remaining elements.

In this article I have made considerable use of various books and articles by F. W. Clarke, T. C. Chamberlin, J. P. Iddings, H. S. Washington, T. K. Rose, and Roscoe and Schorlemmer, and gained most valuable information therefrom. But I wish in particular to express my deep gratitude to Professor James F. Kemp for his personal assistance and encouragement.

REVIEWS

British Antarctic Expedition, 1910–1913, The Physiography of the McMurdo Sound and Granite Harbor Region. By GRIFFITH TAYLOR, D.Sc., etc. London, 1922.

The beautifully printed and luxuriously illustrated monographs (in two series) of the last Scott expedition to the Antarctic owe their air of opulence to the generous sums which were raised by public subscription in memory of Captain Scott and the companions who perished with him. The report before us is the work of the senior geologist and glacialist of the expedition and is perhaps not adequately described by its title. There is but little land exposed in Antarctica, the surface being generally covered by one glacier type or another. The report on glaciology for the expedition was prepared by C. S. Wright and R. E. Priestley, the former the physicist of the expedition, and this report has already been reviewed in this *Journal*. Taylor's report might almost as well be described as glaciology, though with emphasis upon the sculpture of the land, and it is, moreover, restricted to glaciers which are marginal to the inland ice.

At the outset Taylor puts himself upon record as convinced by his own studies, first made in the Alps of Switzerland and later on the margins of the Antarctic continent, that the main sculpturing work of the ice is accomplished, not by erosion, but by the weathering effects of alternating thaw and freeze—nivation; and he brings forward a wealth of maps, sketches, and excellent photographs with which to bolster his conclusions.

With the assistance of his colleagues—Debenham, Wright, and Gran—he prepared maps of the vicinity of McMurdo Sound and Granite Harbor, which, in view of all the difficulties of the work, reflect great credit upon the expedition and give to his conclusions especial weight. To the fretted upland of an advancing hemicycle of glaciation as it became planed off and in part effaced by the overriding continental glacier of a later stage, and now in turn partially laid bare for observation during the receding hemicycle, Taylor applies the apt term "palimpsest" surface. He shows, moreover, that in connection with these now waning marginal glaciers there is a very pronounced local thawing even when the air temperatures are well below freezing, and that in one case a temporary river 25 miles in length (Alph River) was observed.

Most of the peculiar marks in topography of mountain glaciers within moderate latitudes, and many of the characteristic types of mountain glacier, are illustrated in this section of the Antarctic; though with modifications from nourishment and at times by overriding of inland ice as above described. Curious silt and gravel "piers" and deltas along the front of some of these glaciers take the place of the usual moraines.

The monograph is characterized throughout by keen insight and careful observation, based on ample experience and due to much industry. Dr. Taylor is now assistant professor of geography at the University of Sydney, the unique chair of geography upon that continent.

WILLIAM HERBERT HOBBS

India's Mineral Wealth. By J. COGGIN BROWN, superintendent, Geological Survey of India. London: Oxford University Press, 1923.

In this little volume of 120 pages is given an authoritative summary of the mineral wealth of India. Within recent years there has been a remarkable growth in the development of India's mineral resources. The number of mineral concessions issued by the government on state lands has increased from 60 in 1899 to 650 in 1922, and the value of the mineral output, so far as recorded, has increased from roughly £7,800,000 in 1908 to over £30,000,000 in 1920.

Since the publication of a similar summary of *India's Mineral Resources* in 1908, to quote this volume,

> . . . . more coalfields have been tapped by railways and fresh oilfields drilled; the enormous iron ore resourses of Orissa have been partially proved, while a successful iron and steel industry with its attendant subsidiaries has been established; the copper-bearing lodes of Singhbhum have been explored and the production of refined copper commenced; the great reserves of argentiferous lead-zinc sulphides of the Northern Shan States have made Burma the chief new factor in the world's production of lead; the wolfram deposits of Lower Burma, then practically untouched, are now known to be the most important in the British Empire, and supplied the needs of the Allies for the greater part of the war period; the monazite deposits of Travancore, then absolutely unknown, have proved to be the largest and richest in the world. India still heads the list of the world's mica producers, while her deposits of manganese ore have given her the same proud position as regards that mineral from time to time. India now produces gold, silver, lead, copper, iron and steel; petroleum is refined and cement made on a large scale within her borders; her manganese ores are smelted to a degree sufficient to meet the requirements of her iron industry, and a commencement has been made in the by-product coking of her coals.

Seventy-seven industrial minerals are mentioned in the report and the salient features of their production described. Though containing no maps nor illustrations, the booklet contains a number of statistical tables.

E. S. B.

The Geology of the Broken Hill District. By E. C. ANDREWS. Memoirs of the Geological Survey of New South Wales. Geology, No. 8, Supplement. Department of Mines, Sydney, 1923.

A supplement to the large report by the same author on this most important Australian mining district. The rock and mineral assemblages and the geological structures of the principal mineral provinces of New South Wales are briefly described. A summary of the geology of the Broken Hill District is already available to American readers (see *Economic Geology*, Vol. XVII [1902], pp. 470–90). As this summary is prepared by the author of the original report it is hardly necessary to attempt a second summary in this *Journal*.

E. S. B.

Origin of the Tectite Sculpture and Some Consequences. By R. W. VAN DER VEEN. 1923. Pp. 15–41, pls. 6.

The author concludes that the tectites are glasses, sculptured by terrestrial chemical corrosion, and of probably cosmic origin.

A. H. B.

The Devonian of Missouri. By E. B. BRANSON, with chapters on "The Bailey Limestone," by V. O. TANSEY, and "The Little Saline Limestone," by GRACE ANNE STEWART. Missouri Bureau of Geology and Mines, Vol. XVII, 2d series. Pp. x+279+xv, pls. A–H+71, tables 1, maps 1.

The report is largely paleontologic. The initial chapter contains a discussion of the stratigraphy of the Missouri Devonian. The Grassy Creek shale, formerly classed with the Devonian, is referred to the Mississipian, as is also the Sylamore sandstone. Each of the four principal divisions is treated separately as to lithology and relationship to other formations, and the paleontology of each is summarized. Distribution and stratigraphic relations are illustrated by maps and sections. The bearing of the work on paleogeography is indicated by modifications of Schuchert's maps for the successive stages of the Devonian. The

descriptions of species constitute a distinct contribution to the literature. The good quality of the photographic reproductions is a noticeable feature and adds much to the value of the report as a reference work.

A. H. B.

Coal Resources of the Raton Coal Field, New Mexico. By W. T. LEE. U.S. Geol. Surv. Bull. 752, 1924. Pp. 254.

This field is in the northeastern part of New Mexico and is a continuation of the well-known Trinidad (Colo.) coal field. The general geology of the region has been described in previous publications by the same author. The present report specializes in the coals. The most valuable coal seam is of Upper Cretaceous (Vermejo which is pre-Laramie) age. Other more discontinuous and less pure coal seams occur in the overlying Eocene (Raton, equivalent to the Poison Canyon and Denver) beds. The Eocene coal beds are separated into two groups by the "barren series"; the upper group is the more valuable. The coal is "medium rank" (p. 1) or "relatively high rank" (p. 238) bituminous, and "compares favorably with the best bituminous coal of Ohio"; much of it will coke. The heating value averages close to 15,000 B.T.U. In general, the older coal is of higher grade and forms the better coke. The inclosing beds are essentially flat lying and are interrupted by only very minor faults. Post-Cretaceous erosion and Quaternary igneous activity have introduced complications from the miner's viewpoint. During the decade 1911–20 over 27,330,000 tons of coal were produced from this field. Because of the discontinuity of the Tertiary coal seams, no estimate of the available tonnage is given. Over fifty analyses and numerous measured sections, as well as an areal geologic map, are included with the report. The report should be of great aid to operators in selecting places for the future exploitation of the coal of this field.

D. J. F.

Transactions of the Institute of Economic Mineralogy and Petrography. Moscow.

Various numbers of this series, comprising geologic studies of both local and general interest, have recently appeared. A few may be listed: *Geological Sketch of Borjom; The Genetic Relations of the Deposits of Ore in the Krivoi Rog; The Rocks of the Ouvildy Lake, Ural Mountains; A New Method of Preparing Thin Sections; Nephrite from the Mount Bikilar (Ural); The Development of the Asbestos Industry,* etc. These are published in Russian, but a summary in English is included in each paper.

R. T. C.

Marble Deposits of East Tennessee. Tennessee State Geol. Surv. Bull. 28, 1924. Pp. 264, pls. 16, figs. 29.

Part I, by C. H. Gordon, consists of the history of marble quarrying in east Tennessee; the origin, occurrence, and distribution of marble in that region; and the geology and description of the marble areas.

In Part II, T. Nelson Dale describes quite exhaustively the constitution and economic adaptation of the Holston marble, the most important marble of that area. The calcareous sediment from which the marble originated is almost exclusively organic. The great compressive and tensile strength of this marble and its superior hardness and absorption are due largely to evenly distributed minute bryozoa. Among the geologic problems discussed is the nature and origin of stylolites.

Part III, "Marble Quarrying Industry in Tennessee," by Oliver Bowles, is an excellent treatment of the "technology" of the marble industry and should be especially valuable to the quarry operator.

The *Bulletin* is well illustrated and contains colored maps of the Marble Belt.

L. F. A.

Répertoire de la Bibliographie Géologique du Sud-Est de la France (Alpes Françaises et Provence). Comprenant: Les Publications relatives à la Géologie, la Paléontologie, la Minéralogie, la Pétrographie, et les Sciences connexes. Par W. KILIAN et O. NICAUD. Travaux du Laboratoire de Geologie de la Faculte de Sciences de l'Universite de Grenoble, 1923. Tome XIII, Premier Fascicule. Grenoble: Imprimerie Allier, Pere et Fils, 26, cours Jean-Jaurès, 1923.

Fornsjöstudier inom Stångåns och Svartåns Vattenområden med Särskild Hänsyn till den Sen och Postglaciala Klimatutvecklingen. Akademisk Avhandling. Av UNO SUNDELIN. Särtryck av Sveriges Geologiska Undersökning, Ser. Ca N:O 16. Stockholm, 1917.

Om Torvmossar och Marina Sediment Inom Norra Hälsinglands Litorinområde. Akademisk Avhandling. Av BERTIL E. HALDEN. Särtryck ur Sveriges Geologiska Undersöknings Årsbok, 1917. Stockholm, 1917.